Thermal Contraction Lesson
results in
Steel Tunnel Liner Damage

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General Project Overview

Silver Lake Reservoir Complex is a $242 Million project located in Burbank, CA

US Environmental Protection Agency mandated that all open storage reservoirs used for drinking water be protected by covering or bypassing

The project includes both tunnel and open cut steel pipelines connecting two Silver Lake reservoirs which have a combine capacity of 100 Million Gallons

Silver Lake Steel Tunnel Liner

- 120” diameter segmented precast concrete tunnel casing under Griffith Equestrian Park to the Silver Lake Reservoir Complex and installing a 96” x .563” x 3,200’ butt welded steel tunnel liner through the tunnel
- The steel liner was located within the concrete casing providing a minimum 6” annular space which was later filled with 1000 PSI grout.
- After hydro testing both ends of the tunnel pipe were connected to the existing system by conventional cut and cover methods using bell and spigot welded steel pipe.

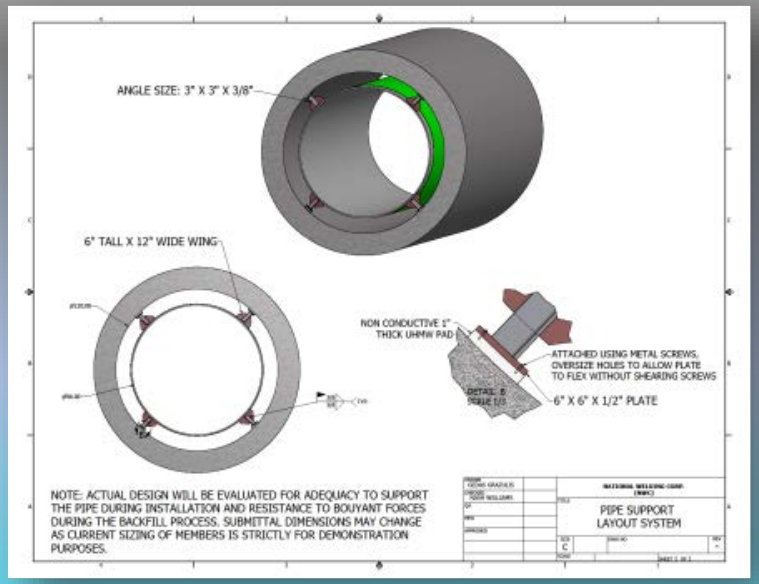
Tunnel Liner Details

- The 96” welded steel liner had a .500” mortar lining and the exterior had a 1” mortar coating over an exterior tape wrap. Coatings were held back 9 inches
- Finished pipe measured just over 2” thick, was 40 feet in length and weighed approx. 46,000 lbs
- Joint design was a butt weld with split steel backing to allow assembly and welding within a tunnel.

Specified Pipe Blocking

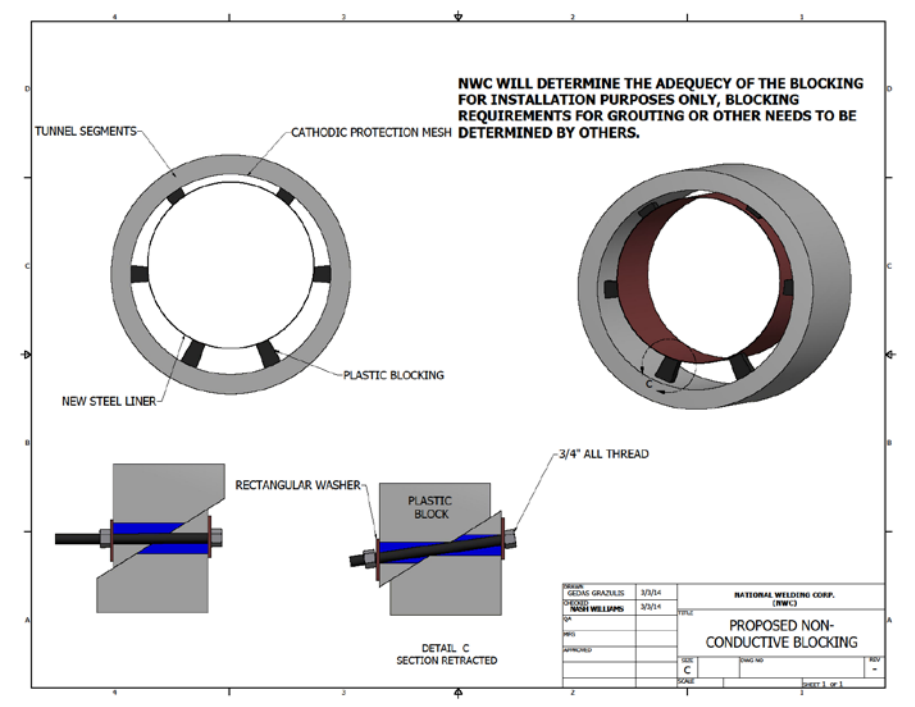
- Specified blocking was a 6” pipe insulator commonly referred to as casing spacer/isolators.
- This type of spacer created concerns in this application including:
  1) Fixed dimensions cannot easily accommodate expected variations in tunnel elevation
  2) Spacers attached to the pipe as permanent bands require a much smaller spacer diameter than the casing inside diameter in order have enough clearance for installation
  3) These spacer do not block the pipe from flotation during annular grouting
  4) Commonly installed by jacking/sliding on the tunnel floor while adding each pipe length at the tunnel portal. This is an issue due to the tunnel length and the cathodic protection system which includes a full circumference expanded titanium mesh at every pipe end.

Alternate Welded Steel Blocking



- Welded steel pipe support was electrically isolated from the concrete casing by UHMW (Ultra High Molecular Weight) plastic pads
- Each joint could be custom fit to the required elevation, providing intimate blocking of the pipe between the ceiling.
- Option was not acceptable as having welded attachments to the steel liner was undesirable to the owner

Accepted Independent Blocking



- Accepted method with 4 independent adjustable HDPE (high density polyethylene) blocks at each pipe end
- Design provided 4 times dead load safety factor for 46,000 lbs sections . **Not intended for axial movement**
- Cathodic protection titanium mesh located at each joint precluded allowing axial movement anyway.
- Method achieved the isolation, non-welded attachment and adjustability required by the designer
- Several masonry bulk heads were installed for grout operation and provided some added pipe support

Tunnel Pipe Welding

- SMAW (Shielded Metal Arc Welding) or stick welding was specified for the project
- Pipe seams included over 25 lbs. of weld metal and anticipated to delay the tunnel liner
- Alternate FCAW-G (Flux Cored Arc Welding with Gas) or Flux Core welding was proposed which is much faster, cleaner and has many superior properties to stick.
- Flux Core was a change to the Specifications and found to be an unacceptable deviation
- Stick welding was utilized and on the first 2000 feet the welding progress rate lagged several weeks behind the installation
- Actual welding time for Stick was found to be 2.5 to 3 times longer than Flux Core welding

Pipe Storage

- Pipe was fabricated well ahead of schedule and subsequently stored in the California desert prior to shipment to site
- Due to limited on site storage only a few day's supply of pipe was delivered at a time

Tunnel Liner Installation

- Project was performed during the hot season (August and September) with mandated around the clock installation
- The pipe was lowered by crane to the installation carrier at the tunnel shaft then transported to the installation location beginning at the far end of the tunnel

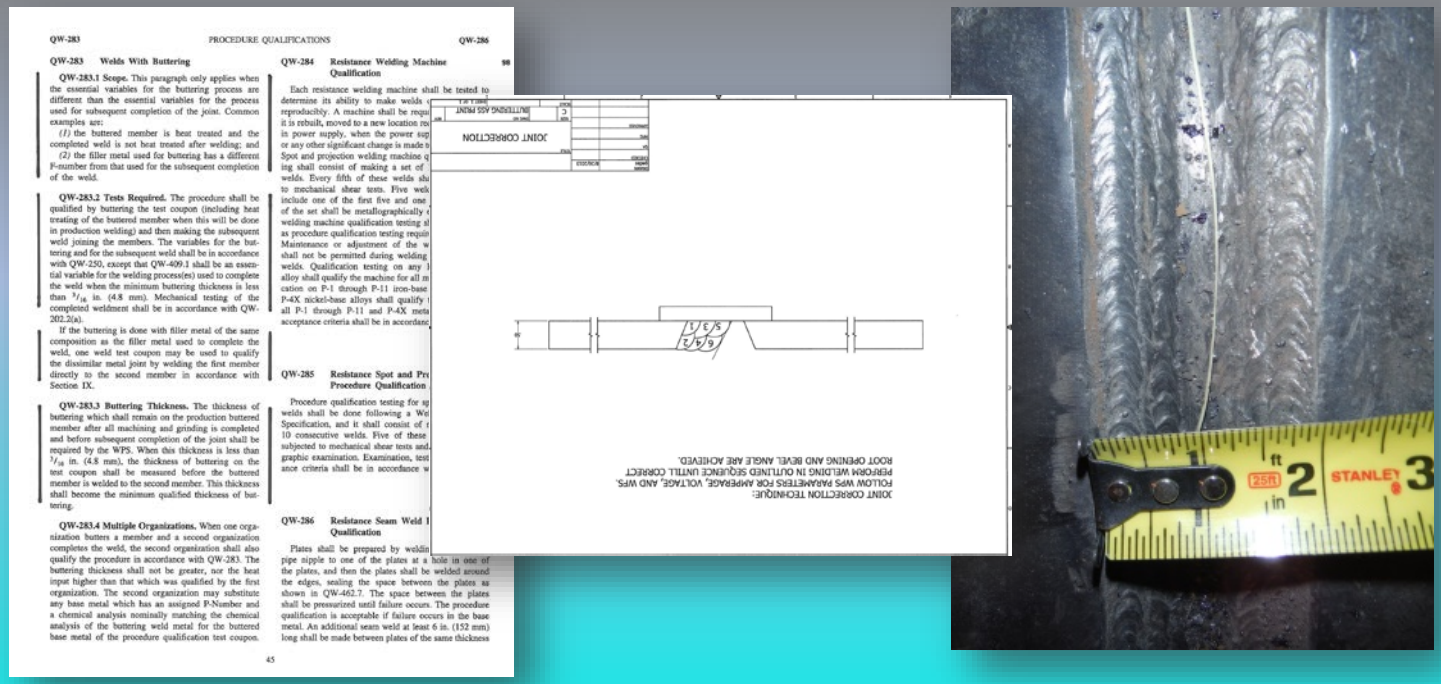
Liner Assembly

- The first pipe was positioned against an I-beam in order to restrain movement of the pipe during placement of subsequent pipe
- Additional pipe installation began with stabbing the incoming pipe onto the previously installed pipe utilizing a butt weld with steel backing
- Pipe was adjusted to the proper line and grade then tack welded or root welded to provide a temporary connection
- After adjusting to the final location the pipe was blocked to prevent further movement and secured for final fitting and welding operations

What Happened Next?

- Approximately 2000 feet or 50 pipe lengths were installed within the first 11 days on an expedited two shift schedule
- During this progress two temporarily tacked/rooted pipe joints began to pull apart in what appeared to be thermal contraction
- The conditions were examined, meetings followed and options explored as follows:
  1) It was apparent these joints acted to relieve the thermal stress as the pipeline cooled
  2) The team considered removing tack welds on previously installed joints to allow contraction but this was rejected as it may not occur in a predictable way and was expected to cause numerous pipe joints exceeding the maximum root tolerance or pulling apart.
  3) Temporary attachments were immediately installed to restrain any further movement, unfinished root welds were immediately completed and additional supplemental weld metal was added to the remaining pipe joints

Remedy for the Oversized Joint



QW-283 PROCEDURE QUALIFICATIONS QW-286

QW-283 Welds With Buttering

QW-283.1 Scope. This paragraph only applies when the essential variables for the buttering process are different than the essential variables for the process used for subsequent completion of the joint. Common examples are:

(1) the buttered member is heat treated and the completed weld is not heat treated after welding; and

(2) the filler metal used for buttering has a different F-number from that used for the subsequent completion of the weld.

QW-283.2 Tests Required. The procedure shall be qualified by buttering the test coupon (including heat treating of the buttered member when this will be done in production welding) and then making the subsequent weld joining the members. The variables for the buttering and for the subsequent weld shall be in accordance with QW-250, except that QW-409.1 shall be an essential variable for the welding process(es) used to complete the weld when the minimum buttering thickness is less than $^{3}/_{16}$ in. (4.8 mm). Mechanical testing of the completed weldment shall be in accordance with QW-202.2(a).

If the buttering is done with filler metal of the same composition as the filler metal used to complete the weld, one weld test coupon may be used to qualify the dissimilar metal joint by welding the first member directly to the second member in accordance with Section IX.

QW-283.3 Buttering Thickness. The thickness of buttering which shall remain on the production buttered member after all machining and grinding is completed and before subsequent completion of the joint shall be required by the WPS. When this thickness is less than $^{3}/_{16}$ in. (4.8 mm), the thickness of buttering on the test coupon shall be measured before the buttered member is welded to the second member. This thickness shall become the minimum qualified thickness of buttering.

QW-283.4 Multiple Organizations. When one organization butters a member and a second organization completes the weld, the second organization shall also qualify the procedure in accordance with QW-283. The buttering thickness shall not be greater, nor the heat input higher than that which was qualified by the first organization. The second organization may substitute any base metal which has an assigned P-Number and a chemical analysis nominally matching the chemical analysis of the buttering weld metal for the buttered base metal of the procedure qualification test coupon.

QW-284 Resistance Welding Machine Qualification

Each resistance welding machine shall be tested to determine its ability to make welds reproducibly. A machine shall be requa it is rebuilt, moved to a new location re in power supply, when the power sup or any other significant change is made t Spot and projection welding machine q ing shall consist of making a set of welds. Every fifth of these welds sh to mechanical shear tests. Five wel include one of the first five and one of the set shall be metallographically welding machine qualification testing s as procedure qualification testing requir Maintenance or adjustment of the w shall not be permitted during welding welds. Qualification testing on any alloy shall qualify the machine for all m cation on P-1 through P-11 iron-base P-4X nickel-base alloys shall qualify all P-1 through P-11 and P-4X meta acceptance criteria shall be in accordanc

QW-285 Resistance Spot and Pro Procedure Qualification

Procedure qualification testing for sp welds shall be done following a Wel Specification, and it shall consist of 10 consecutive welds. Five of these subjected to mechanical shear tests and graphic examination. Examination, test ance criteria shall be in accordance w

QW-286 Resistance Seam Weld Qualification

Plates shall be prepared by weldin pipe nipple to one of the plates at a hole in one of the plates, and then the plates shall be welded around the edges, sealing the space between the plates as shown in QW-462.7. The space between the plates shall be pressurized until failure occurs. The procedure qualification is acceptable if failure occurs in the base metal. An additional seam weld at least 6 in. (152 mm) long shall be made between plates of the same thickness

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JOINT CORRECTION

JOINT CORRECTION TECHNIQUE:
FOLLOW WPS PARAMETERS FOR AMPERAGE, VOLTAGE, AND WPS.
PERFORM WELDING IN OUTLINED SEQUENCE UNTIL CORRECT
ROOT OPENING AND BEVEL ANGLE ARE ACHIEVED.

- The root opening of the two pipe joints root opening increased approximately 1.5” and no longer met the approved Welding Procedure Specification (WPS).
- A new WPS was prepared to correct the joint geometry back to the approved WPS which could then be executed.

Further Examination

DIGITAL INFRARED THERMOMENTER READINGS						
PERFORMED 8-12-14						
SURFACE PIPE				**TUNNEL PIPE**		
STEEL PIPE INVERT	118			STEEL PIPE INVERT	76.2	
STEEL PIPE CROWN	113			STEEL PIPE CROWN	86.5	
MORTAR INTERIOR SHADED	107			MORTAR INTERIOR INVERT	77.4	
MORTAR INTERIOR SUN EXPOSED	127			MORTAR INTERIOR CROWN	82.7	
PIPE EXTERIOR MORTAR SHADED	101			PIPE EXTERIOR MORTAR INVERT	80.9	
PIPE EXTERIOR MORTAR SUN	111			PIPE EXTERIOR MORTAR CROWN	86.3	
				TUNNEL WALL	74.3	
STEEL PIPE AVERAGE TEMPERATURE		115.5		STEEL PIPE AVERAGE TEMPERATURE		81.35
STEEL PIPE SURFACE/TUNNEL DELTA		**34.15**				
LOCAL AREA AVG TEMP HIGH/LOW	**85.14**	**62.86**				
LOCAL AREA TEMPERATURES 7 DAYS PRIOR TO INCIDENT; Aug 4 high 88 low 66, Aug 5 high 87 low 60, Aug 6 high 80 low 61, Aug 7 high 80 low 61, Aug 8 high 85 low 63, Aug 9 high 86 low 65, Aug 10 high 90 low 64. **AVG HIGHS 85**, **AVG LOWS 63**						
NOTE: PIPE TEMPERATURE ARE SHOWN IN DEGREES FAHRENHEIT. MEASUREMENTS WERE TAKEN ON SURFACE PIPE MARK 36 AND TUNNEL PIPE TEMPERATURES MEASUREMENTS WERE TAKEN ON MARK 38						

- Further investigation determined there was a 34 degree (Fahrenheit) temperature differential between the stored pipe on the surface compared to the installed pipe installed in the tunnel which is summarized above
- After gathering the information the temperature delta was entered into an equation for thermal expansion/contraction to evaluate the expected pipe contraction.
- Unfortunately the conclusion indicated there could be additional movement beyond that found in the initial two pipe joints

Calculations

Linear Expansion/Contraction

$\Delta L = \alpha L_o \Delta T$

Given:

ΔT =34.15°F

L_o=24,000 inches

α=6.5x10^{-6}inch/(inch °F) Carbon Steel

So;

ΔL=5.33 inches

Linear Force Calculation

$\sigma = ExKx\Delta T$

Given

E=30x10^{6} lbs/in^2

K=6.5x10^{-6} 1/°F

ΔT=34.15°F

So;

σ=6659.25 lbs/in^2

A=Πx98 inchesx9/16 inches=173.18 in^2

F=σxA

So;

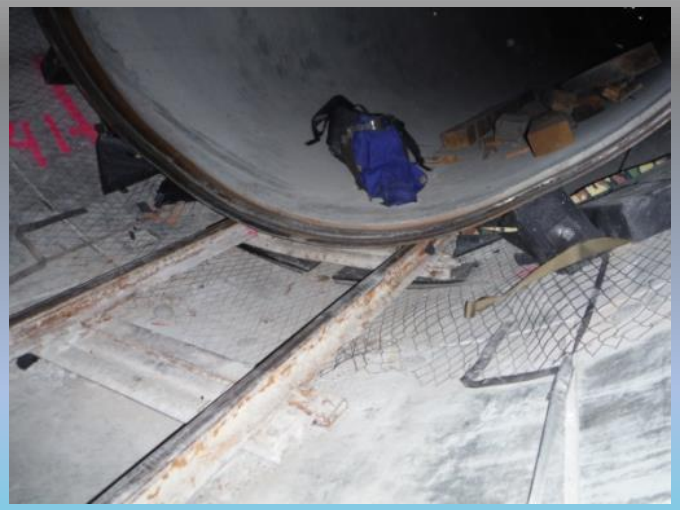
F= 1,153,250 lbs

- The thermal contraction event can be summarized with the expectation of 5.33 inches linear movement (contraction) in the 2000 feet of pipe or .11 inches per pipe length
- Utilizing the Linear Force Calculation we learn the anticipate force will amount to 1.1 million pounds of force
- Both are well beyond the design of the support blocks.

Result of Contraction

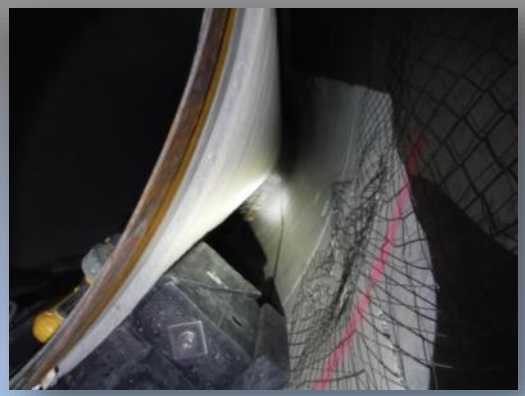
- As indicated by the calculations, and while addressing a plan of action, the same 50 joints continued to contract for an additional 8 days
- Ultimately all 2000 feet of the installed pipe had contracted to the point of toppling the support blocking thereby dropping the tunnel liner several inches within the tunnel.
- Axial load pulled a 3” x 3” x .25” square washer through an 8” x 15” x 16” block of 2800 PSI Compressive strength HDPE

More Damage



- The first pipe installed had contracted away from the blocking I-beam placed by 3.78”
- Ironically, other than changing the pipe elevation within the tunnel, the only detectable damage to the steel pipe was one limited deformation found in last pipe

Remaining 1000 Feet of Tunnel Liner



- The remaining 1000’ of tunnel liner installed on a single shift basis
- Production limited to have the prior installation rate allowed pipe thermal contraction to occur during the slowed process.
- The pipe supports were doubled under each pipe for added measure and the remaining tunnel liner was installed without incident

Design Considerations

1. Welded pipe supports are much more robust than independent blocking and can accommodate axial movement by yielding.
2. Bell & Spigot pipe can accommodate thermal movement much better
3. FCAW (Flux Cored Arc Welding) production out performs SMAW (Shielded Metal Arc Welding or Stick) by a factor of 2.5 to 3 times, which expedites completing the welding and avoids joint separation, but will no direct effect on thermal contraction.
4. Heavy exterior mortar coatings with inner tape wrapping act to insulate the pipe and can delay cooling of the steel pipe core up to 19 days
5. Conventional expansion joints can accommodate this condition but are not practical in tunnels due to limited future access.

Thermal Contraction Lessons

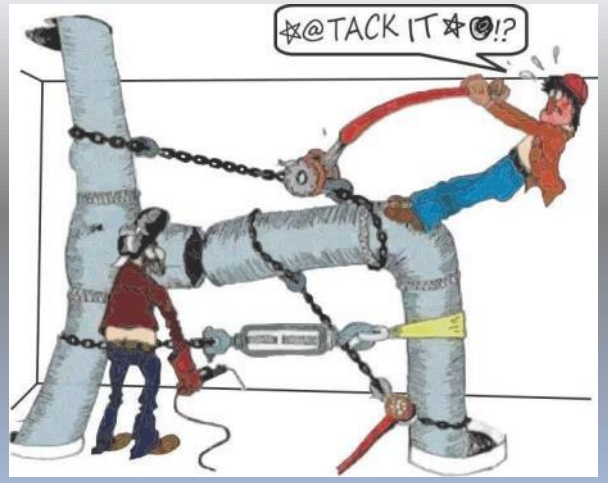
1. Determine the temperature differential between pipe in storage and pipe in the tunnel. Normally an overnight stay will cool the pipe adequately depending on the job location

2. Manually cooling the remaining pipe was considered however shading was impractical because of the limited onsite storage and crane logistics. Water spray to cool the mortar coating was also considered but would add considerable weight and water would adversely affect the weld quality

3. AWWA C206 states “Anticipated thermal stresses should be evaluated by the purchaser” and AWWA M-11 recommends a special closure joints for bell and spigot pipe using a temporarily un-welded joint every 400-500 feet to act as an expansion/contraction joint. This same principle can be adapted to butt joints by utilizing the backing bar or leaving out a short section of pipe until the section has cooled.

Conclusion

Plan ahead



- **Thermal contraction can be a very critical issue** on projects where the pipe temperature during installation is expected to differ substantially from the ground temperature or operating temperature
- **Determine if there is actually an issue** by proactively taking temperature measurements. If there is an issue then the Specifications should provide a means to accommodate or correct the condition
- **Project location, time of year and storage location** of the incoming pipe/materials will all play a part in potential thermal issues
- **The team on this project was very proactive and cooperative** to investigate the cause and consider solutions. As a result of this cooperation by all parties the steel liner was ultimately completed on schedule despite the challenges

Questions

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