Stennis Space Center (SSC)
B-1 Test Facility Liquid Hydrogen Run Tank Vacuum Anomaly & Repair

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LH Tank Background

- 90,000 gallon, 66 psig
- Built in 1962 by Chicago Bridge and Iron Works Company for SSFL
- Relocated from SSFL to SSC in 1984 by barge
- Inner vessel shifted in 1985 during vessel modifications and repaired before being put into service at SSC
- New 12” Run and 8” Fill and Drain Nozzles added and existing nozzles removed in 1985
- Put into service on the B-1 Test Facility in 1988 in support of SSME testing
- Last recertified in June 2004 and is due for recertification in 2014

1985 Vessel on barge at SSC

1985 Damage to Manway Liner

B-1 LH Tank Vacuum System Configuration

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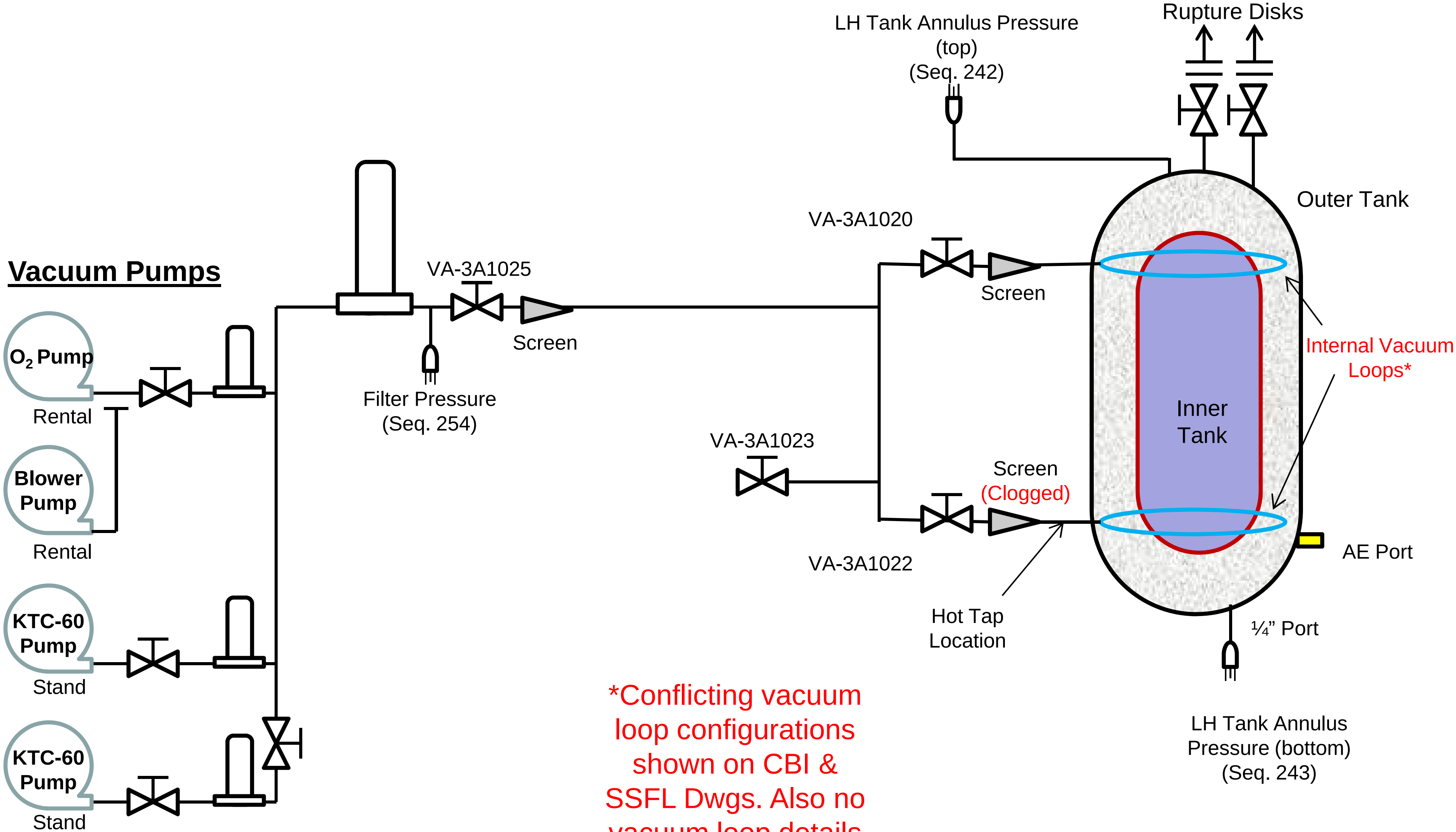
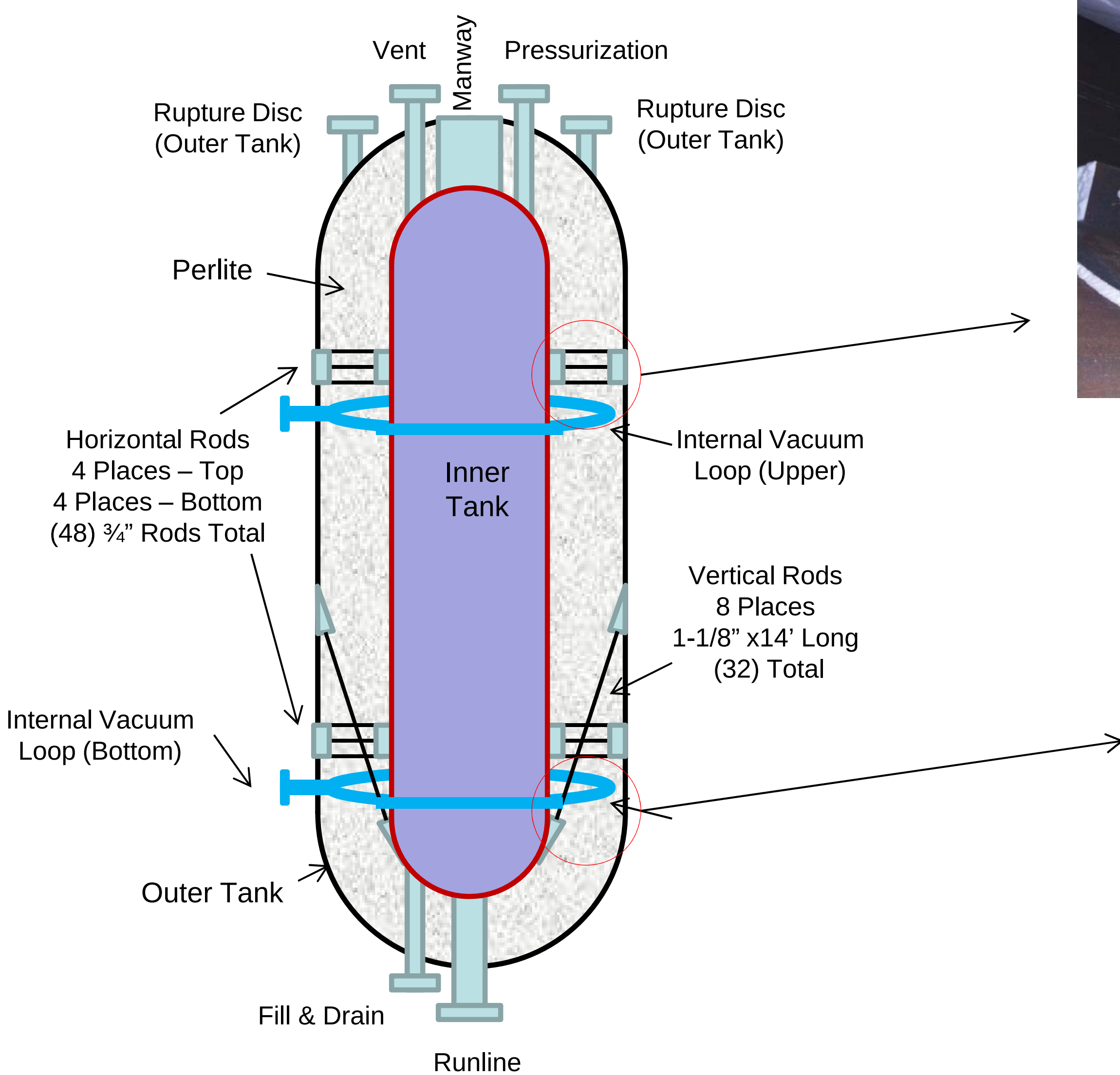


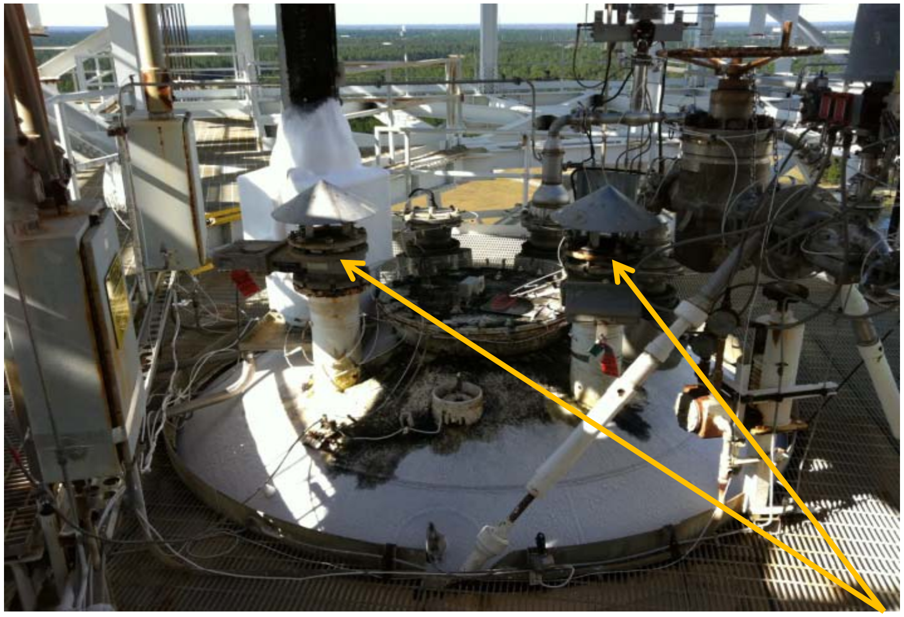
*Conflicting vacuum loop configurations shown on CBI & SSFL Dwgs. Also no vacuum loop details

B-1 LH Tank Inner Details



Anomaly Timeline

- **October 21, 2011**
  - Vacuum issue found
    - Top of the tank – high (>20,000 microns)
    - Bottom of the tank – nominal (<10 microns)
    - Liquid level ~50%
  - Cracks discovered in the two rupture disc holders located on top of the vessel



LH Run Tank (top)

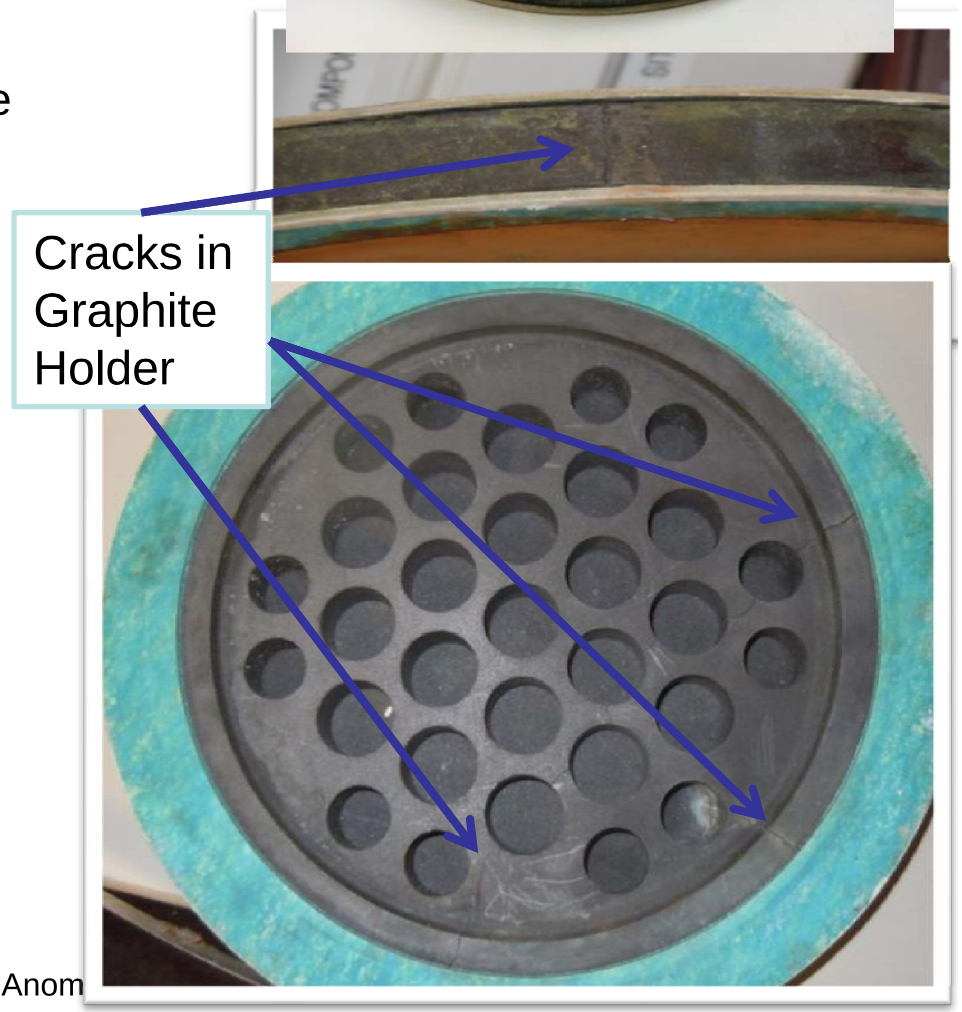
Rupture Discs & Holders

Scenario:

- The cracks allowed an unknown amount of air to enter the annulus.
- The air then froze to the inner vessel outer wall.
- The differential vacuum pressure between the top and bottom annulus indicated compacted perlite and/or frozen air in the annulus.
- High top pressure cause still under investigation. Likely the result of crack growth since previous measurement and/or a vacuum pump being switched off/serviced preceding weekly measurement.

Rupture Discs

- Rupture disc #1 was identified to be leaking via bagging since cracks not visible when installed
- Rupture disc was removed and found to be cracked
- Rupture disc holder was made of graphite and installed in 2003.
- Companion flange was heavily corroded
  - Wire brushing of flange was unsuccessful
  - Flange was sent to machine shop and faced for improved finishing and sealing
- Companion flange and new rupture disc installed
- 2nd rupture disc also leaking but could not be removed due to leaking isolation valve. Utilized Kenny Seal to stop leak.
- No leakage detected via bagging method



Anomaly Timeline (Preps for Hotfire)

- Customer required one more engine hotfire test prior to a three month scheduled outage
- Attempted to remove air (nitrogen and oxygen) in annulus by vaporizing frozen air in annulus:
  - Rented large blower vacuum pump
  - Pressurized inner tank to warm-up tank wall
    - Frozen air sublimated as vessel wall temp rose
  - Monitored/controlled top annulus pressure
- Discovered elevated O2 in vacuum pump discharge. Rented O2 rated pump.
  - After ~24 hrs top annulus pressure dropped
- Conducted tank pressurizations tests to show minimal top annulus vacuum rise (< 5 psia)
- Filled run tank to 100%...top annulus dropped from 1.4 psia (~70,000 microns) to 23 microns
- Set observer cutoff limits on top annulus readings
- Successfully completed two engine hotfires
  - November 2nd
  - November 10th

Rental Pumps

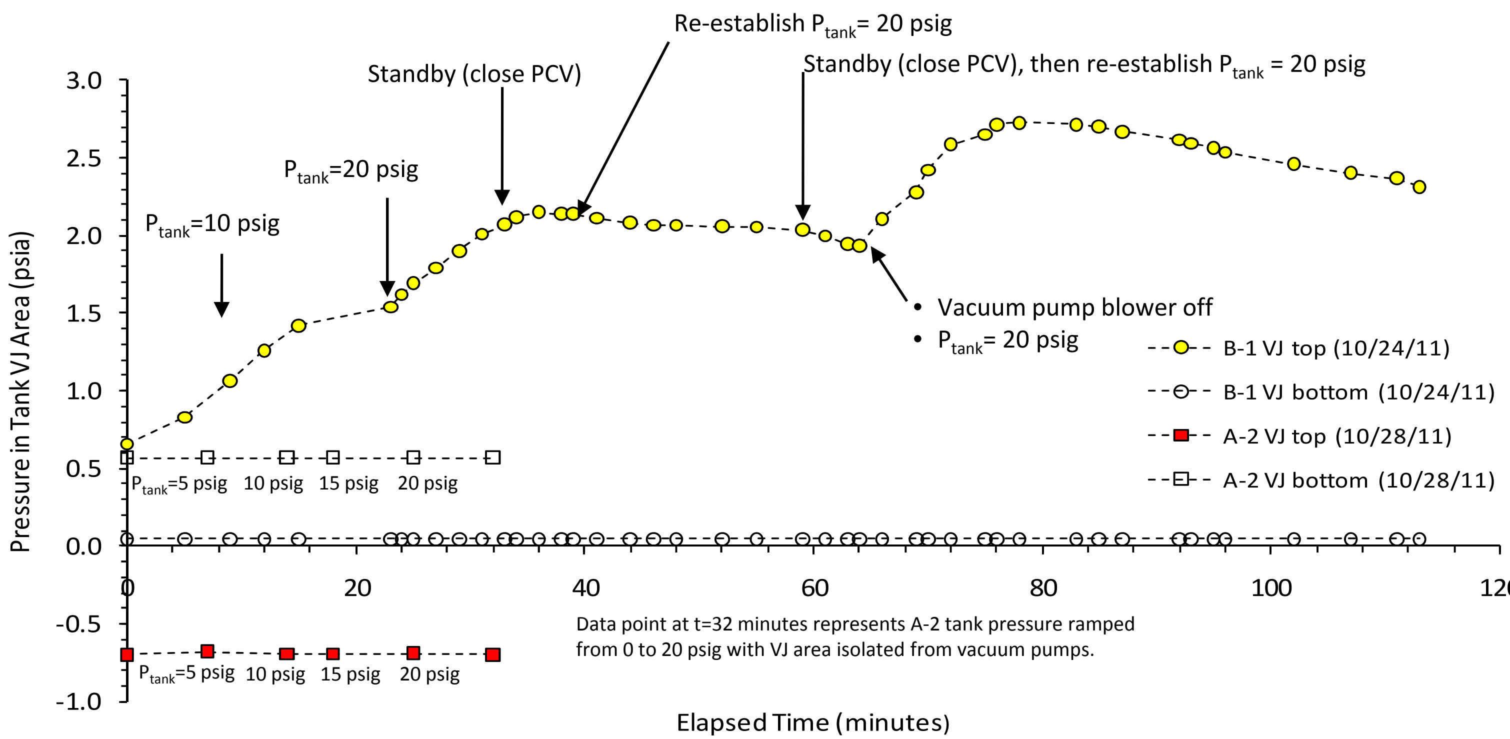
B-1 & A-2 LH Tank VJ Test Data Comparison

Test Objective

- The B-1 and A-2 LH run tanks were pressurized in a series of controlled steps (5 psig, 10 psig, 15 psig & 20 psig) while monitoring the pressures in the vacuum jacket (VJ) area

Results

- The pressures in the A-2 LH tank VJ area did not change as the LH run tank was pressurized from 0 to 20 psig
- The A-2 results significantly differ from B-1 adding evidence of a air filled annulus
- Care and precautions must be taken during detanking due to the frozen annulus



Test Notes:

- A-2 test completed on 10/28/11 using TPS A2-00891; A-2 LH Tank Level ~ 56% full & B-1 LH Tank Level ~ 44% full.
- Vacuum pump exhaust before and after test contained ~ 10.2% O_2; 0% LEL.

Anomaly Timeline (Detanking)

- Precautions were established to drain the tank after the last engine test :
  - Vacuum differential pressure limit established between the top and bottom of the annulus to prevent shifting/damage of the inner vessel (2.5 psid bottom over top limit)
  - Slow emptying of the vessel with continuous vacuum pumping on the top and bottom annulus
  - Two LH barges were stationed at the test facility to refill the LH vessel to lower the vacuum pressure increase if needed
- Began detanking on November 16, 2011
- A combined customer, NASA/SSC, and Test Operations Contract (TOC) team conducted the operations on a 24 hour/7 day a week basis
- Top annulus pressure began to rise.
- 12.5 hours after detanking bottom annulus pressures began to rise
- Bottom vacuum header proved ineffective in controlling the bottom annulus pressure indicating the bottom vacuum header was non functional. Top header had no effect on bottom annulus.
- Contingency processes were implemented to transfer small amounts of liquid hydrogen back into the vessel as needed to lower vessel annulus pressures

Annulus Pressures During Detanking

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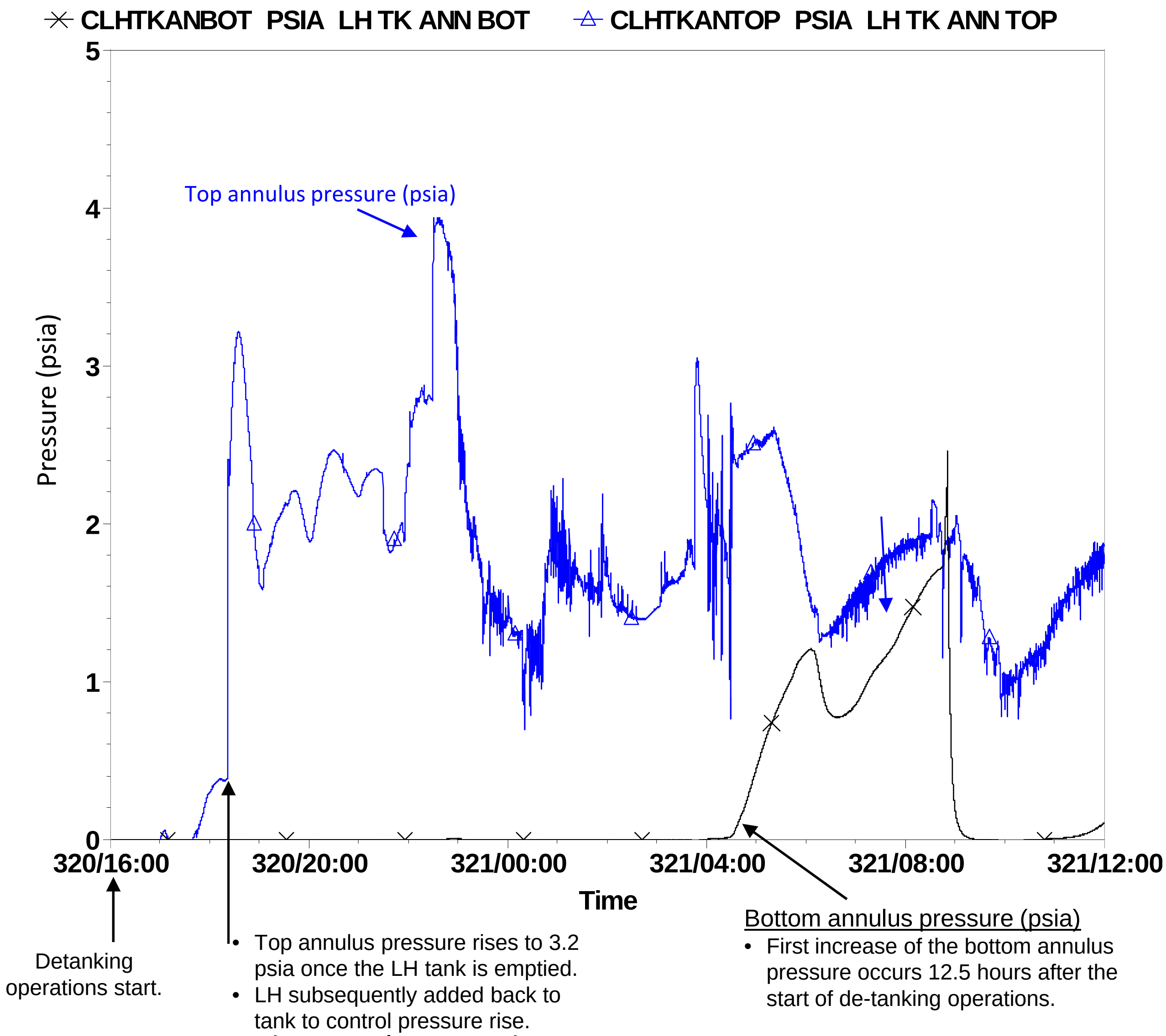
- B-1 LH detanking operations commenced on 11/16/11 (day 320) at 4:00 pm.
- Generally, pressure-vent cycles were performed in addition to emptying the inner tank of LH.
- During the first day of detanking, the top annulus pressure rose sharply to 3.2 psia once the LH tank was empty while the bottom annulus pressure remained at 0 psia.
- The first increase of the bottom annulus pressure occurred on 11/17/11 at 4:30 am, 12.5 hours after the start of de-tanking operations.
- Pressure-vent cycle at 10:45 am (11/17/11) yielded a vent gas temperature of ~140°R.



Anomaly Timeline (Frost/Ice Buildup)

November 18, 2011

- Two days after detanking heavy ice/frost developed on the bottom of the outer vessel
- The vessel bottom temperature continued to drop into the 140-160 Rankin, consistent with liquid air temperatures
- Well below the 410 Rankin ductility range for the carbon steel material subjecting the outer vessel to cracking at any time

Bottom of LH Run Tank at Low Temperature

Anomaly Timeline (Attempts to Establish Pumping Capability)

- Attempted to establish pumping ability on bottom annulus
- Utilized existing instrumentation outlet on the bottom of the outer vessel
- Resulted in limited pumping capability due to the small (1/4”) available connection size

- AE port
- Upon initiation of pumping vacuum, large amounts of perlite were pumped from the annulus resulting in continuous cleaning of facility vacuum system filters

- “Hot tap” drilling device was designed, fabricated on site, and utilized to drill into the existing bottom vacuum header immediately adjacent to the outer vessel bypassing any clogged external filters

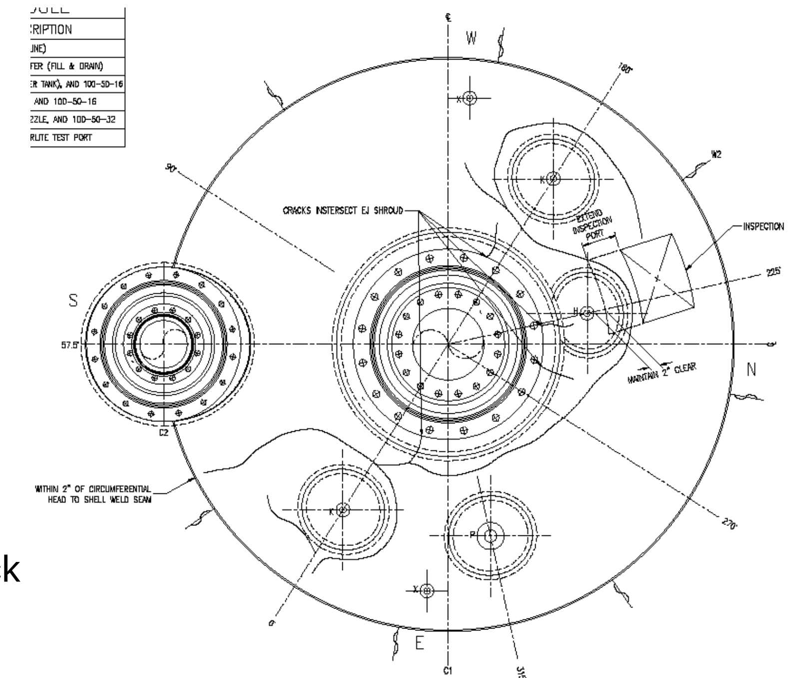
¼” Instrumentation Port used for Vacuum Service

Plug Removed for Vacuum Connection to AE port

Anomaly Timeline (Rupture of Bottom Head)

- At 10:05am on December 4, 2011, during preparation for installation of the external perlite filtering system, an audible “pop” emanating from below the tank was heard by the test crew
- The on stand test crew was evacuated into the protective concrete hard core of the test facility and then evacuated to the test control center through the instrumentation tunnel
- Video and instrumentation data at the test control center showed a release of vapor from the bottom of the vessel through a crack accompanied by an immediate slow rise in the vacuum annulus pressure at the bottom of the vessel.

Crack



LH Tank Bottom

Crack in Outer Tank Timeline

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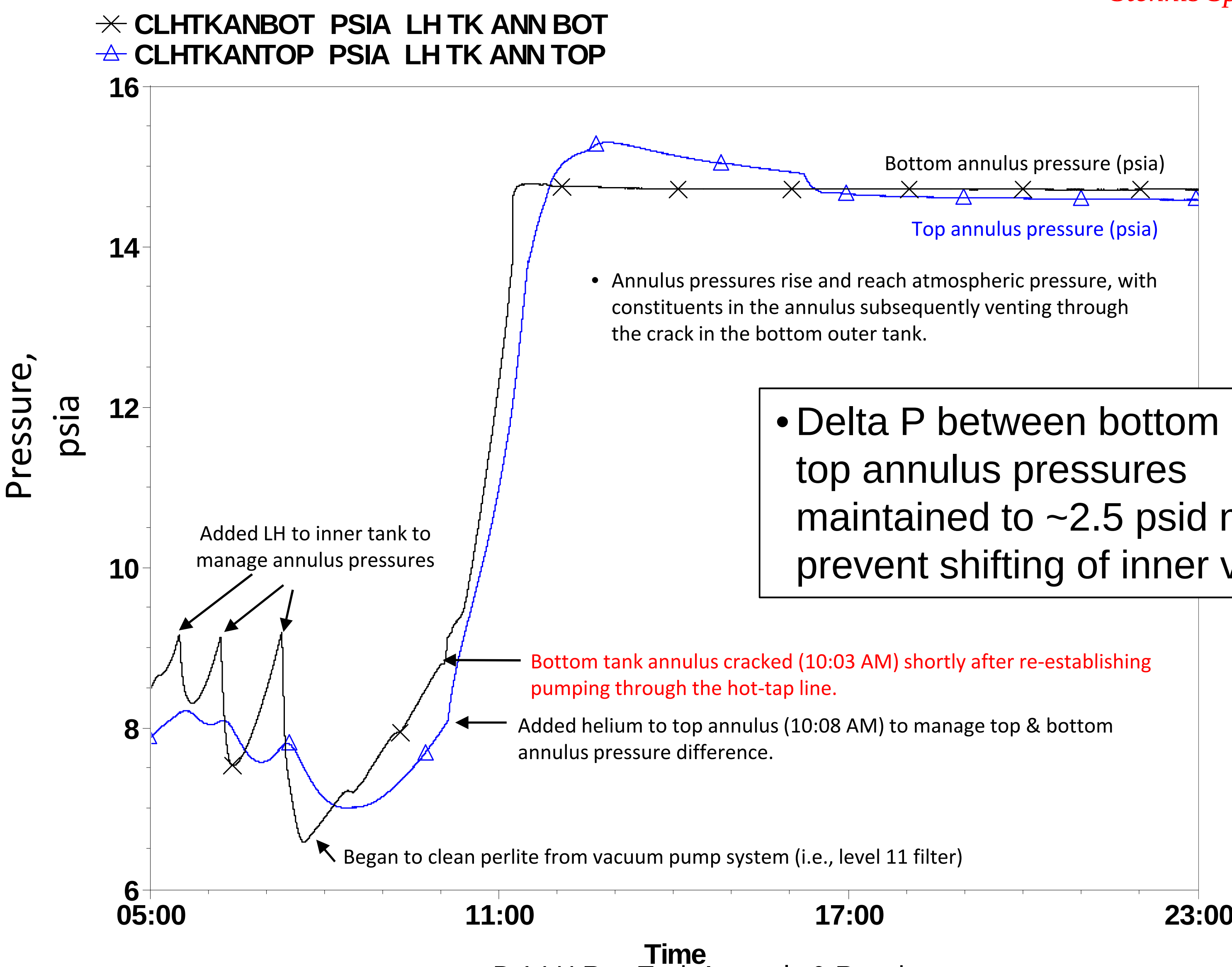


- Delta P between bottom and top annulus pressures maintained to ~2.5 psid max to prevent shifting of inner vessel

What We've Learned

- Lower Vacuum Header
    - Physically disconnected inside annulus
    - Made from flexible hose
    - Lower witch's hat screen plugged
- Previous Issues with Tank at SSFL (prior to 1970)
    - Vacuum issues: 6000 micron minimum
    - Iced over vessel bottom during detanking
    - Cracked bottom head area
- Compacted Perlite
- Full vessel will cryopump annulus and show good vacuum
- Inner Vessel
    - Successful Acoustic Emissions test
    - Successful structural support inspections
- Outer Vessel

    Numerous cracks identified in smaller lower head

    No issues found in main lower head

Lower Vacuum Header Disconnected

Vacuum Header Flexible Hose

Witch's Hat Screen

-1

B-1 LH Tank Vacuum System Internal Manifold Redesign

Concept

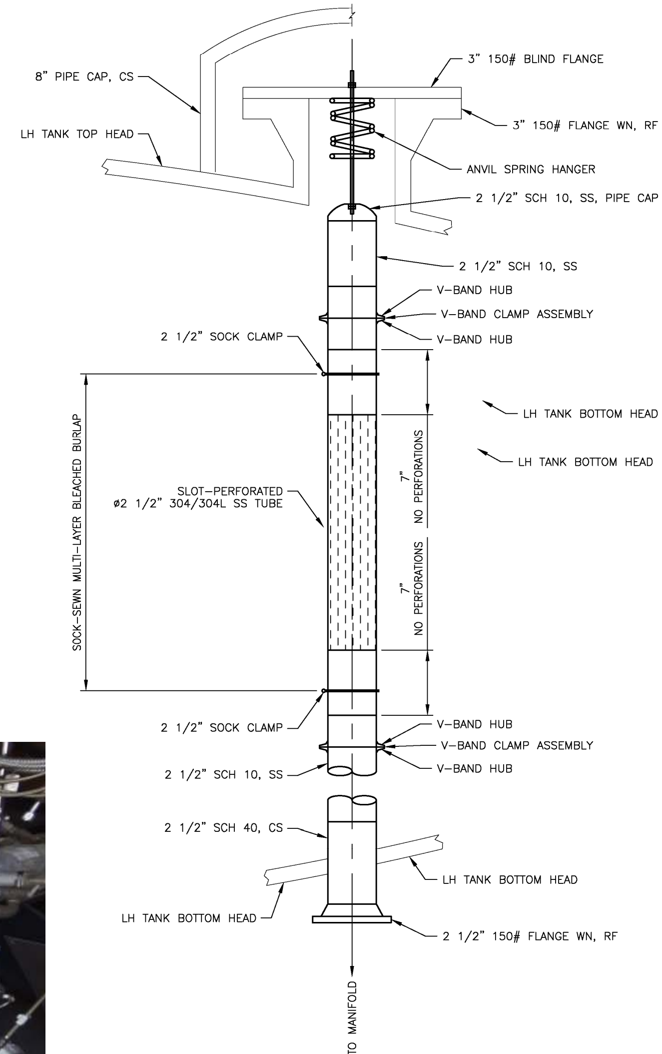
- 4 internal vertical manifolds
- Suspended on spring on one end, welded on other end
- Sections of perforated or slotted tubing covered with sock filtration material

Pros

- High surface area (greater than current B-1 system)
- Manifold traverses tank vertically allowing internal equalization of pressure on top and bottom
- Significantly fewer tank penetrations (less expensive, faster, and few welds that could leak)

Cons

- No experience on site with vertical vacuum manifold
  - Industry contacts confirm use of vertical vacuum manifolds is not uncommon



ELEVATION DETAIL
(ø2 1/2" MANIFOLD PIPING VACUUM CONCEPT)
SCALE: N.T.S.

Future Improvements

- Rupture disc replaced by lift plates
- Preventative maintenance on lift plates
- Weld or install weld caps on mechanical joints where possible (i.e., perlite fill nozzles)
- New vacuum header design
    - Allow better top/bottom communication (i.e pressure can equalize in the annulus)
    - Better accessibility to components
- Prior to future detankings
    - Verify no massive air in leakage by monitoring top annulus pressure while performing pressurization cycles
- Better vacuum monitoring
    - Remote top and bottom readings
    - Automated alarms
- Standardize pumping operations
    - Isolate vacuum system post LH loading
    - If pumps are needed then investigate for air in leakage

Questions?