Title: Q2R18 Concerns Related to Steam Dryer

Unit(s): Quad Cities Unit 2

Event Date: 03/29/2006
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I. Executive Summary:

During the planned in-vessel visual inspection (IVVI) of the Quad Cities Unit 2 (U-2) reactor steam dryer at the beginning of refueling outage Q2R18, a crack was discovered in the dryer skirt at the 140° azimuth location. At the completion of all dryer inspections, cracks were discovered at various locations in the dryer assembly including the dryer skirt base ring, a vane bank end plate, chevron plates, and a latch box. Several of these cracks occurred in areas adjacent to one of the two areas most severely deformed during removal of the dryer in May 2005.

This Root Cause Analysis (RCA) investigation scope was focused on determining the causes of the dryer assembly cracking in the dryer skirt plate, the vane bank endplate, and the latch box assembly. RCA investigation into the events associated with the design, fabrication, installation and operation of the steam dryer identified a series of factors that, when taken in aggregate, are the causes for the formation of the identified cracks. The causes for each of the three cracks included in the scope of this RCA is summarized below:

1. Steam Dryer Lower Skirt Crack at 140°: The root cause for this cracking is related to deformation caused when the dryer skirt base ring caught on the reactor pressure vessel (RPV) dryer support lugs in May 2005 (referred to as the "lifting event"). The exact mechanism of initiation of the cracks could not be determined, however the RCA concludes that this event introduced significant plastic strains that reduced the material's fatigue endurance properties. When combined with the cyclic loadings that the dryer experiences during normal operation, fatigue cracking propagated through the skirt base ring and into the dryer skirt panels. The lifting event occurred as a result of changes in design of the installation hardware used in the replacement dryer. This change in installation hardware is considered a root cause. These changes, combined with widened installation clearances introduced during dryer fabrication (referred to as "ovality") allowed for enough movement for the dryer to become damaged on the RPV support lugs during removal. The widened installation clearance introduced from fabrication ovality is also considered a root cause for the dryer skirt cracking.

2. Cracking in Gusset 19 of Vane Bank "E" at 320°: Root cause is: having very little weld metal between the end plates, proximity to a weld transition (Stress Riser), fabrication stresses due to hood assembly and weld shrinkage, and the presence of operating vibration loads.

3. Cracking in Latch Box at 220°: Root cause is: high residual weld stress from weld end discontinuity and the corner location.

Corrective actions include:

- Repair of the most severely damaged portions of the dryer skirt and base plate near the 140° azimuth.
- Replacement of skirt and base plate material in the 220° azimuth area, which did not exhibit cracking but was considered to have similar potential crack initiating factors as the 140° azimuth areas.
- Modification of the dryer base plate to reduce the potential for future lifting events.
- Modification of the dryer guide slots to reduce the potential for future lifting events.
- Repair of the crack in the dryer latch box at the 220° azimuth.

- Evaluation of the visual indications (crack) in the bank E drying vane end plate. Evaluation concluded that there was “adequate justification for continued operation of the steam dryer without repair of the cracking at the gusset to vane bank end plate locations …” (Ref. 17)
- Modified main steam relief valve branch lines with acoustic side branches to reduce dryer cyclic loads.

An extent of condition review included inspections of other susceptible areas of the steam dryer. All dryer cracking was reviewed in accordance with IVVI program requirements regarding actions required prior to restart from Q2R18, and appropriate inspections in future outages. The key analysis documents for these determinations are listed in Attachment 8 of this RCA. No other degradation similar to the three events in the scope of this RCA was identified. Analyses completed by General Electric (GE) and reviewed by Exelon determined that without the additional stresses and material degradation resulting from the May 2005 lifting event, the operational loads were not sufficient to initiate cracking in the U-2 dryer skirt plate. Therefore, similar cracking of the Unit 2 dryer is not expected to occur in the future. In addition, the Unit 1 steam dryer, which did not experience either fabrication ovality or installation lifting events, did not exhibit similar cracking when inspected in the Q1M19 outage in May 2006.

The steam dryer degradation was not reportable, however the issue has been discussed with the Nuclear Regulatory Commission (NRC). A risk assessment of the identified condition was performed and determined the consequences of this event had minimal impact on reactor safety. Although unanticipated structural cracking was identified in the dryer, the cracking did not represent an increase in risk to nuclear safety or off-site dose consequences. A Probabilistic Risk Assessment (PRA) evaluation found this event to be non-risk significant.

II. Condition Statement:

During the planned IVVI in Q2R18, the RPV steam dryer was removed from the vessel and inspected. Initial inspection revealed a branching crack in the dryer lower skirt area approximately 6 feet in total length at the 140° azimuth location (Refs. 10&11). Subsequent inspections also identified cracking in the steam dryer vane bank end plate in the "E" bank (Refs. 12&13), and a crack in the lower right corner of one dryer latch box (Refs. 14&15). These three conditions form the specific investigation scope requiring resolution in this RCA, and are referred to in subsequent sections of the RCA as:

- **Event 1**: Steam Dryer Lower Skirt Cracking near the 140° azimuth, identified in AR 472321.
- **Event 2**: Steam Dryer Cracking in Gusset 19 of Vane Bank "E" End Plate near the 320° azimuth, identified in AR 473034.
- **Event 3**: Steam Dryer Cracking in Latch Box near the 220° azimuth, identified in AR 475369.

Additional dryer cracking was identified during Q2R18, and although not specifically included in the scope of this RCA, all dryer cracking was reviewed and dispositioned in accordance with IVVI program requirements. Specifically, actions required prior to restart from Q2R18 were completed, and appropriate inspections in future outages were specified. The key analysis documents for these determinations are listed in Att. 8 of this RCA.

Consequences & Significance: The dryer is a passive non-safety related component, however, it must remain structurally intact to preclude introduction of loose material into plant systems such that no safety-related systems, structures or components are prevented from performing their design basis safety function. Additionally, the dryer skirt must function as a boundary to maintain the basis for reactor water level sensing and protective actuations. At the time of discovery, all dryer components, including the skirt, remained constrained within the dryer envelope and therefore, there was no safety significance to this event.

This report focuses on the equipment failure, the failure modes, and causal factors for the identified dryer issues. The failure of the skirt plate has the potential to generate debris, for which a lost part evaluation (Ref. 20 is the Lost Parts Evaluation for this condition) was completed for Unit 1 impacts. This event is not considered a recurring problem since the Unit 2 dryer is a newly installed replacement. OPEX reviews have not identified previous history with large cracking in dryer skirt plate material similar to that identified in Q2R18. Quad Cities Unit 1 has a similarly designed installed replacement dryer and Dresden Units 2 & 3 have similar replacement dryers that are not yet installed. These three additional dryers will be considered for extent of condition in this RCA.

III. Event Description:

Note: This event description provides a chronological narrative of the sequence of events as they apply to this RCA. This section also includes "Notes" intended to highlight the significance of the information as it applies to the subsequent Analysis and Evaluation sections. Additional items included in this RCA report, which may assist in general understanding of the events, include:

Att. 1: Event and Causal Factors Chart.
Att. 2: Event Timeline Table.
Att. 3: List of References.
Fig. 1: General Steam Dryer Configuration
Fig. 2: Schematic of Steam Dryer Base Ring to RPV Lug Orientation

<u>2004 – Early 2005</u>

Following several previous Quad Cities outages in which steam dryers were found with failed or degraded dryer elements, a decision was made to purchase and install new steam dryers in both units.

The steam dryer was fabricated and assembled at U.S. Tool and Die in Pittsburgh, PA under the direction of GE. Due to transportation limitations, the steam dryer could not be shipped in one piece in the required timeframe. This required that the dryer be fabricated as two assemblies that were shipped separately and then assembled locally.

Note: During the design and fabrication of the new Quad Cities steam dryers, several issues imposed constraints on the delivery of the first dryer for Quad Cities. Manufacturing delays necessitated that the dryer originally intended for Quad Cities U-1 installation during Q1R18, be delivered for installation in Unit 2 during Q2P03.

<u>March 2005</u>

The Unit 2 replacement steam dryer upper half (vane banks and support ring) and the skirt assembly were welded together at J. T. Cullen in Fulton, IL.

<u>3/30/05</u>

The Configuration Change Review Checklist (CC-AA-102 Attachment 10F) for the dryer modification EC351168 Revision 0 was signed by the Reactor Services department representative.

Note: This was the initial end user's review in the Exelon design process. This review is considered a "cross discipline" review and a barrier to prevent negative impacts of design changes. This review was documented after dryer fabrication was almost complete. This topic is discussed further in the evaluation section.

<u>3/31/05</u>

Inspection of the dryer at J.T. Cullen following assembly determined that the as-built dryer dimensions were outside the expected design tolerances. The diameter measured across the 0°-180° orientation measured 245", while the 90°-270° orientation measured 249". Welding distortion was noted as the cause. Laser measurements of the assembled dryer were conducted and confirmed that QC2 dryer base was approximately 2 inches out of round.

Note: Subsequent sections of this RCA refer to this as the "ovality" issue.

4/25/05

GE Deviation Disposition Request (DDR) 431002828-27 (Ref. 7) was approved, accepting the dimensions of the base plate as-is. Investigation determined the dimensional deficiencies resulted from welding performed at J. T. Cullen, which resulted in distortion of the dryer mid-support ring, skirt and base plate. The DDR noted that the dryer will fit in the vessel despite this ovality. Normal clearances were "compromised" so additional guidance constraints were placed in the lower guide block to limit misalignment and assist in installation.

Notes: 1. The additional constraints noted above are the guide rod spacer blocks installed under Field Disposition Instruction (FDI) 0085 (Ref. 9)

2. This DDR addressed the dimensional issues due to the ovality but did not address potential residual stresses in the dryer as a result of this distortion.

4/26/05

The U-2 replacement dryer was transported to the station and subsequently moved to the reactor building refueling floor.

4/26/05

Exelon Nuclear Fuels determined that the replacement dryer dP will be less than the original dryer (original dryer dP was nominally 0.3 psid versus an expected dP of 0.1 psid on the replacement dryer). This change has an impact on Minimum Critical Power Ratio Operating Limit, and on the ASME overpressure results. Root cause analysis on these issues is assigned under IR 330331 (Ref. 37).

Note: The subsequent RCA concluded: "the root cause of the event was a lack of information on the project team regarding the sensitivity of non-structural analyses to the dryer dP value.

5/4/05

The Configuration Change Review Checklist (CC-AA-102 Attachment 10F) for the dryer modification EC351168 Revision 1 was signed by the Reactor Services department representative.

Note: This was a second user's review in the Exelon design process. This review is considered a "cross discipline" review and a barrier to prevent negative impacts of design changes. This topic is discussed further in the evaluation section. This review was documented after the dryer was already fabricated and staged on the Quad Cities Refueling floor.

05/07/05

Unit 2 shutdown for Q2P03 for the main purpose of installing the replacement dryer.

5/11/05

During initial installation in the U-2 reactor vessel an interference was encountered that prevented setting the dryer onto RPV dryer support lugs. At approximately 2.5" above the dryer support lugs, the overhead crane cables went slack and the dryer assembly shifted towards North (approximately 110° azimuth). The dryer was lifted and the vessel area inspected without identifying the source of the interference. Upon restart of the descent, the dryer again stopped and shifted towards North.
The dryer was raised slightly to allow further detailed inspection. A camera inspection inside the skirt revealed that the inner diameter of the dryer skirt base plate was interfering with the steam separator

guide rods. Although the overall outer diameter of the dryer assembly was not changed by the new design (Ref. 1), the skirt inner diameter is smaller with the base plate protruding farther towards the center of the dryer than the original design. This resulted in the interference with the separator guide rods, with the skirt base plate contacting the two guide rods located at the 20° and 200° azimuths. Installation activities were stopped and the Outage Control Center (OCC) was notified of the issue, and discussions were initiated to determine resolution of this problem.

> Note: The U-2 replacement dryer exhibited limited clearance between the RPV dryer support lugs and the cutouts provided in the base plate ring. As the dryer is lowered, the skirt base plate must pass all four of the support lugs. The width of a support lug is 3 inches, while the width of the base plate cutout provided is 4-inches, leaving a nominal ½" clearance on each side of the lug. This presented a known challenge and plans were to use additional care to field verify that acceptable clearance existed, or modify the clearances as needed. While the dryer was lowered into the RPV for the first time, the GE Product Line Manager was stationed in the reactor cavity to monitor the clearances. It was confirmed during this initial lowering that the clearance between the base ring cutout and RPV lugs was small, but the dryer had been installed without incident until the interference with the separator guide rods was identified.

<u>5/12/05</u>

When the interference between the separator support rods and the base plate was identified and the dryer could not be installed, it was decided that the dryer would be removed from the RPV to allow modification of the base plate. The OCC recovery and action plan for the dryer removal discussed the tight clearance issue with the oncoming crew. Instructions were provided to the oncoming refuel floor crew performing the dryer lift to watch the RPV lug clearance very closely due to the tight clearance.

During the lift for removal of the dryer, the base plate impacted the vessel support lugs despite the increased scrutiny, including performing the lift slowly, as evidenced by multiple stops. Att. 7 describes in detail the sequence for the base plate contact with the RPV support lugs. At the time of this dryer lift, the load cell display for the overhead crane was not functional (overload cutout circuits were functional), so there was no ability to estimate the impact load based on floor observations. Workers reported visual evidence of a high load on the lift cables from the noise and rapid cable movement when the load sprung free. When the dryer was set on the decontamination pad, visual damage to the base plate was evident and the OCC was notified.

Inspection of the base plate showed a downward deflection/distortion in the dryer base plate from its normal flat horizontal shape. These downward bends were recorded as 3/4" at the 140° location, 5/8" at the 220° location, and 5/16" at the 320° location (Ref. 1).

A detailed discussion of what occurred during this "Lift Event", along with pictures of the damage are provided in Att. 7.

<u>5/13/05</u>

Prompt Investigation Report 334348 (Ref.4) on the dryer damage was performed and presented to MRC on 5/13/05. This report reviewed the sequence of events, and detailed the observed damage as follows:

1. Marks on the bottom of the base plate at the 20° position
2. Mark (burr) on the inside of the base plate at the 220° position
3. At the 40° and 140° positions, seismic shim blocks were noted to have shifted and were scratched
4. Raised metal on 3 clearance slots

5. Wear on one RPV support lug

Items 1 through 3 were believed to have occurred when the dryer shifted towards North as it contacted the separator guide rod. The prompt investigation described conflicts or problems with:

1. Original tolerances did not allow the separator guide pins to clear the ID of the dryer base plate.
2. Traveler Package KCZKU-INSTALL-1 stated that special care should be taken to verify no interferences exist, as well as the need to maintain the dryer level and to watch the overhead crane load cell for deviations
3. The overhead crane load cell was not functioning.

This prompt investigation concluded that the base plate damage was caused by interference with the separator guide rods and RPV support lugs.

> Note: The prompt investigation addressed the fact that the dryer could not set into place due to contact with the separator guide rods. It noted that the cause of the damage was not known at this time (this was handed off to the subsequent ACE). The prompt did not discuss the effects of the damage to the dryer from the lifting event.

<u>5/15/05</u>

To eliminate the interference between the separator guide rods and the skirt/base plate, cutouts were provided in the dryer skirt and the base plate at the 20^{o} and 200^{o} azimuth locations. (WO732708-01 / GE Field Deviation Disposition Request (FDDR) RMCN06243, Ref. 29). The cutout of the partial penetration weld was seal welded at the cutout and examined via PT exam.

The damage to the base plate was evaluated and found acceptable by GE, an independent third party review, and Exelon for use-as-is (Ref. 1 & 8). FDDR RMCN 06245 included instructions for the material cleanup and disposition of the as-left deformations. The indications caused by the contact with the RPV lugs during the dryer removal were removed from the metal surfaces of the dryer and examined via PT exam prior to reinstalling the dryer in the reactor vessel.

> Note: This RCA reviewed this FDDR, and the supporting documentation, and noted a lack of detail in documenting both the inspection and analysis activities completed to resolve this issue. *Because this RCA concluded that the transient imposed on the base plate and dryer skirt was a causal factor for the subsequent cracks during operation, it must be concluded that the Q2P03 review (May 2005) was a missed opportunity to determine the actual state of the dryer. This topic is discussed in more detail in the Evaluation section.*

<u>5/16/05</u>

Unit 2 was started up and operated at EPU and pre-EPU power levels during the remainder of the fuel cycle. No apparent complications to Unit 2 operation due to steam dryer issues were observed during this operating cycle, and the dryer cracking condition was not evident until reactor disassembly for Q2R18 in March 2006.

<u>5/25/05</u>

An ACE (Ref. 2) for the steam dryer lifting event was completed and approved on this date. This RCA reviewed this ACE in detail following the identification of cracking in Q2R18. The results of this review are discussed in the Evaluation section.

This ACE also noted the fact that the crane load cell was not working at the time of the May 2005 dryer lifting event, concluding that that this was not a significant factor in the apparent cause. (Note: The load cell was repaired May 16, 2005 prior to placing the dryer back into the vessel (WO 805641-02)).

A GE Root Cause Analysis (Ref. 6) was provided on 5/25/05. This report determined that the cause of the interference between the base plate and the steam separator guide pins was that the dryer design process did not ensure that fit-up problems did not exist. This occurred because the Computer Aided Design (CAD) model was not adequately developed. The GE RCA noted that several GE design engineers had initially identified the potential for interference at the separator guide pins, but had failed to revisit the concern prior to completion of the dryer design.

<u>3/28/06</u>

U-2 shutdown for refueling outage Q2R18. While performing IVVI during Q2R18, the cracks were discovered on the steam dryer that led to the initiation of this RCA. The scope of this RCA includes (references noted are for the original Exelon Corrective Action Process (CAP) Issue Report (IR) numbers, and the GE Indication Notification Report (INR) numbers):

Event 1- The large crack in the dryer skirt at the 140° azimuth (Ref. 10, 11)
Event 2- Dryer "E" bank end plate crack at 320° azimuth. (Ref. 12, 13)
Event 3- Latch Box crack at 220° azimuth. (Ref. 14, 15)

In addition, all four steam dryer lifting eyes were discovered out-of-position, with one lifting eye exhibiting thread damage to the lifting rod. This issue was originally in the scope of this RCA, but it was determined that the lifting eye concerns were not related to the dryer cracking issues. For this reason, the lifting eye issue was removed from the RCA scope, and transferred for evaluation as a separate Equipment Apparent Cause Evaluation (EACE) (AR# 471848-05). A summary of the results of this EACE appears below:

<u>Summary EACE 471848-05: Dryer Lifting Lug Rotation</u>

Apparent cause: The design of the lifting eye retention method was inadequate to ensure positive engagement. The design provided no ability for ensuring adequate alignment. The recess was located on the lifting rod, which was contained within the threaded connection once the lifting eye was threaded on. The design relied entirely on external orientation of the lifting eyes, which provided no positive verification. In addition, the dimensions of the recess provided minimal opportunity for successful engagement.

Corrective Actions:

1. Modify/Install design of Quad Cities Unit 2 Steam Dryer Lifting Eyes to provide more robust anti-rotation. (Completed before start-up from Q2R18)
2. Modify/Install design of Quad Cities Unit 1 Steam Dryer Lifting Eyes per EC 360571. (Scheduled for completion during Q1M19 in spring 2006).
3. Similar corrective actions will be completed on the Dresden replacement dryers prior to installation.

Identification of Missed Opportunities:

This RCA used the information presented in this event description (and the associated Event and Causal Factors chart in Att. 1) to identify potential issues and missed opportunities for earlier detection, or prevention of the three events in the scope of the RCA. These items are listed below and became the subject of more detailed analysis described in the next section.

Missed Opportunities for Earlier Detection or Prevention of Dryer Cracking:

1. Inadequate inspection of the May 2005 damage: Actions were identified in Ref. 1 & 8 to perform a liquid penetrant test (PT) of adjacent welds. The Field Deviation Disposition Request [FDDR] (Ref. 8) was not clear in identifying specific welds to be inspected – it just specified, "all adjacent welds in the areas that were distorted shall be subjected to PT examination". Interviews with QC personnel determined that only adjacent welds on the outside diameter (OD) of the skirt were PT examined. The weld between the vertical skirt plate and the horizontal base plate on the ID of the skirt was not examined either visually or via PT. This was a missed opportunity to determine the integrity of the base material and weld integrity on the skirt inside diameter (ID) and thus we cannot conclusively eliminate the skirt ID as a crack initiation site. The lack of inspection of the ID of the skirt also eliminated the potential to find the "dimpled" section of the skirt at the 140 and 220° locations which may have led to further analysis of the residual stress placed on the metal.

2. Inadequate disposition of May 2005 damage: In the original dryer design effort, the lower skirt hardware was included in the modeling as a "super element". That is, because the as-designed load conditions on the dryer skirt are typically low and the size of the finite element model was already excessively large, the skirt details below the water line were not included in the finite element calculations with fine nodal granularity. The entire lower area is modeled as a lumped mass and stiffness matrices in the finite element calculations. This is appropriate if the service conditions stay inside the assumed "as-designed" bounds. However, once this portion of the unit had been subject to permanent, localized damage, a rigorous evaluation would have considered whether the dryer was subject to future degradation. This was not specifically included in the disposition of the damaged area.

3. Deficiencies in Design Change Development: A fundamental change in the design of the dryer caused the outer diameter of the dryer shell skirt plate to be reduced, in order that the drain channels could be on the exterior of the dryer assembly. (Note that the outer diameter of the horizontal skirt base plate was the same. The vertical skirt shell plate was reduced.) Exterior drain channels were used in an effort to reduce minor cracking commonly experienced in the area of internal drain channels in earlier designed BWR steam dryers. In addition, because the more robust replacement dryers were heavier, the designers looked for non-structural areas where weight could be reduced. For these reasons, the original design use of 2 continuous guide channels for both of the dryer guide rods, and (4) guide channels for the RPV support lugs were eliminated. These channels were each changed from being a continuous vertical guide path along the height of the dryer skirt, to being two-point (top and bottom) alignment connections (Dryer guide slots for alignment with the RPV guide rods), and Base Ring cutouts to pass through the RPV support lugs. The original guide channels for the RPV support lugs had the same 4" wide clearance as the new dryer's base plate notches. The implication of this is that the tight tolerance on the rotational alignment is enforced at all axial positions during movement. It is this enforcement of rotational alignment that was compromised by the removal of the guide

channels. The 4" wide notches in the base plate only "enforce" this alignment while the base plate is at the elevation of the RPV lugs, setting up the potential for misalignment at other dryer elevations. This, in conjunction with the small clearance (the RPV lugs are 3" wide, so the average clearance is ½" on each side) increase the probability that an impact would occur, by making a higher demand on the users to obtain the simultaneous alignment without impact. Thus a negative consequence of the revised dryer design sacrificed a tolerant and self-correcting configuration for a less tolerant configuration that invited interferences.

4. Fabrication "Ovality" Issues: Fabrication deficiencies had already been identified prior to the May 2005 lift event. These deficiencies resulted during the welding of the two halves of the QC2 dryer at J. T. Cullen. This assembly process resulted in distortion of the dryer mid-support ring, skirt and base plate.

   The distorted as-built dryer base plate condition was identified, evaluated and addressed prior to shipping the dryer to Quad Cities under a Deviation Disposition Request (DDR) (Ref. 7). Corrective measures were taken to prevent this distortion in the assembly of the subsequent dryer assemblies (QC 1 dryer). The distorted QC2 dryer was evaluated and accepted for use, with actions to install additional guidance constraints on the lower guide blocks. (Refs.7&9). This evaluation focused on vessel clearances for installation and removal of the dryer but did not address potential for induced stresses on the dryer components resulting from the distortion.

   Despite the completion of these corrective actions to accommodate installation and removal of the distorted QC2 dryer, the assembly distortion still contributed to the excessive clearances between the dryer and dryer guide rods, and was cited as one of the two apparent causes in the ACE for the May 2005 events. These conditions indicate two missed opportunities:

   - The potential for installation alignment issues was recognized after the "ovality" was identified but corrective actions were not successful in preventing the lift event.
   - The potential for internal metal stresses induced from the "ovality" was not formally addressed in the DDR, FDDR, EACE, or EC's reviewed during this RCA.

IV. Analysis:

Several root cause analysis techniques were used in this investigation. Initially, an Event and Causal Factor Chart (Att. 1) was created to document the known sequence of events, and conditions. This document was used to identify an initial strategy and direction, including the decision to divide the concerns into three issues (Dryer Skirt Crack, Dryer End Plate Crack, and Lifting Lug Concerns). The investigation team then used Failure Modes and Effects Analysis (FMEA) to identify potential failure modes. These potential failure modes were documented on a Complex Troubleshooting Failure Mode Tree (FMT) (ref. MA-AA-716-004, Att.2 pages 3 and 4). Each failure mode was then broken down into potential causes with associated validation and action steps. These actions were then prioritized according to the probability of the failure mode being a causal factor and the availability of data (some validation steps were able to be completed early in the investigation while others required additional time for analysis). The FMT's for Event 1 and Event 2 appear in this report as attachments 5& 6 respectively.

The Lifting Lug Concerns were later determined to be a separate issue from the Dryer Cracking and transferred from the scope of this RCA to EACE AR# 471848-05. For this reason the FMT related to the lifting lug issues is not included as an attachment to this RCA. Similarly, as the Q2R18 dryer inspections continued, and additional issues were identified, the Latch Box Cracking near the 220° azimuth was added to the RCA scope as Event 3 based on a potential linkage to the other two issues. A new FMT was not created for this event because it was evident that the analysis and strategy used for Event 1 (Skirt Crack) and Event 2 (End Vane Bank Crack) were appropriate and bounding for Event 3 (Latch Box Crack).

The FMT charts identified a set of low probability and higher probability failure modes. The lower probability items were set aside allowing a focus on the higher probability items which included:

- Design related issues where the analysis used might have underestimated the loads the replacement dyers would be subject to, and also underestimated the stress conditions resulting from the skirt base cutouts.
- Design related issues that effected the resulting "lift event".
- Fabrication errors, which resulted in the skirt base ring ovality.
- Installation damage resulting from the "lift event".

These probable failures modes were reviewed using additional RCA tools such as: TapRoot®, Cause and Effect Analysis, and Barrier Analysis. The RCA also utilized a significant amount of technical analysis including metallurgical testing of samples of the U-2 Dryer skirt and baseplate, and computerized structural analysis. This analysis is described in more detail below:

A. Structural Analysis Summary:

Detailed finite element models of the dryer skirt and other dryer components were developed or upgraded. Multiple elastic and inelastic finite element analyses were run to simulate the conditions that would have caused the observed deformations. These simulations were used as sensitivity evaluations such that some postulated loadings could be eliminated (i.e., if the loads and stresses resulting from some scenarios couldn't have caused the observed deformation, the scenario could be eliminated). Some of these analyses were used to approximate the material condition resulting from these events and to assess the extent of the possible degradation.

1. The original full steam dryer finite element model contained a super element for the submerged portion of the skirt and water. The skirt in the super element did not have the detail of the base plate cutouts or gussets located on either side of the cutout. A local solid 3D detailed finite element model was created for analysis of the failure location. The analysis validated that the cut out modeling was not significant in determining the skirt stresses & modal response. (Ref. 29)

2. More detailed elastic-plastic analysis of the skirt cutout and gusset areas at 140° was completed. This analysis predicted 17.3% strain at the top of the gusset in the skirt panel. Strain at the edge of the gusset in the cut out was 4%, which corresponds to 55-60 ksi using elastic-plastic analysis. (Ref. 21) This analysis also estimated the amount of loading needed to cause the observed deformation from the list event to be 47,000 pounds.

3. An analysis was completed to estimate the corresponding reduction in the fatigue stress limits in the 140° azimuth Dryer Skirt Crack as a result of the lifting event. Excerpts from this analysis report (Ref. 40) appears below:

> " … given the higher plastic strain and complementary increase in strength of the deformed base ring location, the expected fatigue endurance properties would be significantly reduced due to mean stress effects. This effect can be calculated directly from the equations used by Manjoine, et al [Ref. 41 of this RCA]. Although the region of interest was cold worked by the installation event [referred to as the "lifting event" in other sections of this RCA], the evaluation of the mean stress effect was performed based on the fatigue properties of annealed material. Therefore, the evaluation should be viewed in qualitative rather than quantitative terms. For conservatism, the loading was considered as stress controlled in the determination of the mean stress effect, i.e. the range of Pl + Pb +Q was assumed to exceed 27.2 ksi. The impact of an assumed residual (mean) stress of 60 ksi would be a 30% reduction in the allowable while the assumption of a 70 ksi yield strength to represent the local mean stress would reduce the allowable by 50%. These levels of reduction in fatigue properties are very likely given the deformation and the constraint imposed by the several intersecting welds present at the base ring cut out corner-solid gusset-skirt region where crack initiation occurred."
>
> "In summary, the plastic deformation would be expected to lead to a high residual mean stress. Consistent with the understanding of fatigue behavior in the presence

of high mean stresses, the fatigue endurance limit would be reduced. Based on the conservative evaluation, the reduction in endurance limit would be expected to be a maximum of 50%."

3. Hydrodynamic and acoustic loading on the dryer were re-evaluated. Ref. 21 noted that the turbulent water loads acting on the dryer skirt were not analytically evaluated, but the skirt is in a relatively quiet region near the vessel wall. This indicates that any loading on the skirt from the feedwater flow and separator flow will be a turbulent buffeting from the mixing of these flow streams below the skirt. Since the replacement dryer skirt design should be more able to resist these turbulent loads (replacement dryers used 3/8" thick vs. 1/4" thick plate and the drain channel design/fabrication moved the weld away from the discontinuity), it can be concluded that the water loading on the replacement dryer skirt would not present any fatigue issues.

The July 2005 report on "QC U-2 Replacement Steam Dryer Stress and Fatigue Analysis Based on Measured EPU Conditions (Ref. 35) was reviewed and it was noted that there are additional hydrodynamic loads, assessed to be too low to be of consequence. An acoustic load frequency at 155 Hz appears on the strain gauges and accelerometers and based on the magnitude of the response in power spectral densities is the most dominant mode in the reactor. This mode has been attributed to the Electromatic relief valve (ERV) stub tube resonance and is included in the load basis for the analysis.

Further modal analysis concludes that the failed skirt does not have modes in the low frequency range. This means that while the loads may be impacting the dryer, they are not driving structural resonances. In addition, these frequencies would affect the entire dryer, not just the skirt panel. This results in a conclusion that these loads are not a causal factor in this RCA.

4. A detailed stress analysis of the dryer lifting event was completed (Ref. 36). The analysis report concluded: "In this analysis the lifting forces were applied unevenly in various configurations on the full dryer finite element model in order to assess if the lifting event could have caused crack initiation in the vane bank end plates and/or latch box. The results indicate that no lifting cases could initiate a crack in either the inner vane bank end plates or latch box corner."

B. Follow-up Inspections Summary

1. The inside of the dryer skirt at the 20° azimuth where previous damage from impact with the separator guide rods had been noted were re-inspected and evaluated. This evaluation concluded that the damage was small with no deformation of the base ring. While the minor damaged was repaired, the conclusion remains that impact in this area was not a causal factor in any of the cracking events in the scope of this RCA.

2. The inside diameter of the dryer skirt ring was re-inspected and evaluated at the 140°, 220° and 320° areas. The 140 ° area already required repair of the identified skirt and base ring cracking. The 220° area had a similar amount of base ring and skirt plate deformation as the 140° area, but no observable cracking. The similar deformation was

the major factor in the decision to cut out and replace the deformed material at the 220° area despite no observable cracking (Refs. 27 & 32). The 320° area had gusset deformation less than half that at the 140° location, and no ID skirt or base ring deformation so this area was analyzed to leave "as is".

C. Metallurgical Analysis Summary:

Cut out samples of the cracked areas of the dryer skirt were sent out to GE's metallurgical labs at Vallecitos, CA. The purpose for the testing was to determine the following:

1. Site of crack initiation
2. Mode of crack propagation
3. Material characteristics germane to the investigation
4. Likely cause of cracking

The results of these examinations were documented in "GE-NE-0000-0052-9666, QC U-2 Replacement Steam Dryer Metallurgical Evaluation" (Ref. 19). In addition GE completed a separate evaluation of the Transgranular Stress Corrosion Cracking (TGSCC) identified in these metallurgical samples in the report listed as reference 16 to this RCR.

Excerpts of the Executive Summary and selected sections from the metallurgical report is report are reproduced below:

> **Executive Summary of GE Metallurgical Evaluation (Ref. 19)**:
>
> During inspection of the replacement steam dryer at Quad Cities Unit 2 during Q2R18, cracking was observed in the skirt and base plate at the 140 degree location. Samples were removed from the dryer and sent to GE's Vallecitos Nuclear Center for further evaluation.
>
> Visual examination of the samples showed a relatively smooth straight fracture in the skirt plate, consistent with a fatigue mechanism. Examination of the sample taken from the base plate to skirt plate weld confirmed the fatigue cracking mode. No evidence of ductile tearing (i.e., overload) was found. Near the inner diameter (ID) of the base plate, the fracture exhibited slight twisting, which suggests there was a torsional component to the loading by the time the crack progressed to the ID. The cracking appeared to have initiated in the base plate region and progressed upward into the skirt plate. Although no clear initiation site could be identified, the fracture most likely initiated near the OD of the base plate.
>
> Optical metallographic examination of the skirt plate-to-base plate weld cross sections showed two key features: (1) the root areas of the ID and OD welds contained lack of penetration; and (2) transgranular, branched cracking characteristic of transgranular stress corrosion cracking (TGSCC) initiated from the root area and propagated into the skirt and base plate in both the 140 and 220 degree sections. Neither feature, however, could be identified as an initiator of the

observed fatigue cracking. Some increase in hardness was noted in the skirt plate, consistent with the observed deformation. The material chemistries were consistent with austenitic stainless steels.

Based on the observations, the material failed by mechanical fatigue, initiated towards the OD of the base plate region. Given the deformation observed in the samples examined, the stresses introduced into the cut-out region by bending and the location of the cracking, it is likely that the lifting event contributed to the observed failure.

<u>Excepts from Discussion Section of GE Metallurgical Evaluation (Ref. 19):</u>

Subsequent SEM (Scanning Electron Microscopy) examination of the fracture surface confirmed the transgranular nature of the cracking, consistent with fatigue. All regions that were examined were consistent with a fatigue cracking mechanism, with no evidence of ductile overload found. Some lack of penetration was noted in the weld root, which is consistent with the partial penetration weld geometry specified for the skirt to base plate weld. Inclusions in the weld root were also identified; based on the EDS [Energy Dispersive Spectroscopy] analysis, these inclusions most likely resulted from the original welding process, and were not associated with the failure.

Optical metallography confirmed that the welds were fabricated with at least two passes, which is consistent with the partial penetration weld geometry specified for the skirt to base plate weld. In addition, lack of penetration in the weld root was observed in all of the six cross sections examined. Optical metallography also confirmed that the material was in a solution annealed condition, with some evidence of strain hardening in the base plate, as determined by microhardness. The areas of apparent strain hardening are consistent with the deformation from the lifting event. The cracking mode was transgranular with small secondary cracks, consistent with a fatigue mechanism.

One additional observation was the presence of transgranular cracking in the weld root region of both the 140 and 220 ° samples. Given the branched nature, along with the presence of multiple indications in both the skirt and base plate regions, the most likely cause is TGSCC. TGSCC requires three factors to be present: (1) wetted environment; (2) aggressive species (e.g., halogens); and (3) stress.

Wetted environment: At the 140 degree location, the weld root crevice was exposed to the environment

Aggressive species: Given that the partial penetration weld was made by a flux-core process and weld fluxes typically contain fluorides for fluidity and wetting, the presence of fluorine in the weld root is not unexpected. In addition, the manufacturer of the weld flux confirmed that approximately 3% fluorine was present in the welding flux.

Stress: Significant stress would be present from welding. [The deformation from the lifting event was also a source of stress.]

Since all three factors are present, TGSCC is the most likely cause of the observed transgranular, branched cracking in the weld root. Two factors, however, indicate that TGSCC did not contribute to initiation of the fatigue cracking: (1) On the fracture face, the transgranular cracking was consistent with fatigue. There were some secondary cracks, but no major network of secondary branched cracking that would characterize a TGSCC crack was found, and (2) the initiation region (see Figure 3-3(b) in Ref. 19) does not appear to be in the root of the weld. The directional features indicate initiation on the OD surface. The laboratory examination confirmed that the primary fracture was one of mechanical fatigue; however, the exact initiating location could not be identified.

Key Conclusions from GE Metallurgical Analysis

The GE metallurgical analysis proved to be a key component in this RCA. While the exact initiation mechanism of the dryer skirt plate could not be identified, the results did eliminate several of the potential failure mechanisms, and supported a determination of most probable causes. This included the conclusions below:

1. Skirt plate cracking is consistent with fatigue cracking.
2. There is no evidence of ductile tearing.
3. Cracking appears to have initiated in the base plate region and then propagated into the skirt plate.
4. The fracture most likely initiated near the OD of the base plate.
5. TGSCC was observed in samples from both the 140° and 220° regions, but in neither case was the TGSSC identified as an initiator of the fatigue cracking.
6. Deformed areas exhibited some increase in metal hardness.
7. Material chemistries were consistent with austenitic stainless steel.

D. Interview Summaries:

Interviews were completed with a number of key positions associated with this RCA. This included personnel from: Exelon Reactor Services, GE Installation, and GE Design personnel. A summary of the information from these interviews appears below:

A. Reactor Services:

1. Use of Crane Load Cell Scoreboard:

- Originally installed as a corrective action from an OPEX event where a Dryer was attempted to be removed with only 3 of 4 hold-downs unlatched.
- Typical use of the scoreboard is that the weight of the component will be known and significant deviations will indicate a potential hang up of the load.

- If a significant change in expected load displayed occurs the “Technical Director” (TD) would be monitoring the display and would signal an emergency stop.
- For the Dryer installation the TD’s were GE Supervisors.
- The Signal person for the load moves was typically a Venture Boilermaker assigned to the GE crew.
- Would an available scoreboard have made a difference in this event? Unsure – The Dryer lifting rigs are all metal components so any increase in load would occur very quickly, likely before a response could be made by a lift crew, even in slow speeds. In other lifts where synthetic lifting slings are used, the response time might be longer. (In this case, there is a potential that a load cell change could be responded to when the dryer metal starts to deform, and possibly before the deformation would become permanent.)
- The load cell display has been unreliable since installation. Several outages included lifts made where the scoreboard was inoperable.

2. Dryer Issues:
   - What are the “key points” in a Dryer lift (term noted in several IR’s associated with this event)? A: Aligning the Dryer guides with the guide rods, and the interface between the RPV lugs and the Dryer support ring are considered key points of this lift now and historically.
   - Rx. Services was aware that the full-length guide channels that existed on the old dryer no longer existed on the new dryers.
   - Rx. Services had limited formal involvement with the design of the new dryers (i.e., did not participate in the project team).
   - Rx. Services personnel signed off on the new design because they believed that it could be made to work with some additional care. They also were aware that GE personnel would supervise the initial Dryer insertion and that modifications would be made if needed to support successful installation and removal of the replacement dryers. (Some of the fit up issues would need to be field verified especially during the first installation).
   - Initial insertion of the new dryer allowed for a person to be located in the Refueling bulkhead to assist in alignment. This option will not be available in future lifts because they will be done underwater for dose control.

B. GE Personnel:

<u>Dryer Project Installation Personnel</u>

1. What was included in the pre-job brief for this evolution? A: The pre-job brief prior to the initial dryer move focused on the movement from the refuel floor to the vessel, since this was an abnormal move and resulted in various load path issues. It also included discussion of the dryer clearance issues and that the dryer

design was different and would require significant monitoring while being installed.

2. What process document covered this lift (procedure, traveler, etc.)? A: The traveler provided the direction for initial installation of the dryer - Rev. 0 for the initial move and Rev. 1 for the final installation following modifications. The removal for modifications was performed per the station reactor disassembly procedure.
3. What were considered “key points” in this lift? Were they formally documented? A: There were hold points when the dryer base ring was at 6-inches above the RPV lugs and again when the mounting block was 6-inches above the RPV lugs.
4. Why was the inoperable load cell scoreboard considered acceptable? A: It is not unusual for load cell/displays to be malfunctioning at various plants.

<u>Dryer Project Design Personnel</u>

- The Dryer design was changed from full-length channels was to accommodate relocating the drain channels from the inside of the dryer skirt to the outside of the dryer skirt. To be able to fit in the vessel, the skirt diameter was reduced to make room for the drain channels on the outside of the skirt. Full-length guide rod channels previously integral to the skirt could no longer remain.
- The replacement dryer design uses a 4-point contact design which also minimizes weight increase. The new dryers are more structurally robust through the use of heavier material. The increased weight has to be maintained within the structural capabilities of the existing RPV dryer support lugs.
- This installation hardware is consistent with the design of newer GE BWR’s. There has been no experience of a similar “Lift Event” in these newer BWR’s.
- The ovality event was noted as a factor in degrading the alignment of this QC U-2 replacement Dryer.

V. Evaluation:

This evaluation section is organized as follows:

A. Table of all Causal Factors that this RCA concluded influenced this event.

B. Additional discussion of the basis for cause determination.

C. Discussion of other event conditions that were evaluated as potential causal factors, but rejected, how they were eliminated as causal factors, and their final disposition (no action required, addressed in "Programmatic/Organizational Issues, addressed in "Other Issues" section)

The final section C is needed because this RCA required extensive technical and analytical review and in some cases, cause determinations relied on elimination of other causes to support the RCA conclusion of root and contributing causes.

<u>A. Table of Causal Factors</u>

Problem Statement	Cause (describe the cause and identify whether it is a root cause or contributing cause)	Basis for Cause Determination
Event 1: Crack & deformation of dryer base plate and skirt identified in Q2R18.	CF1a: Lift Event– Design factors: 1) New dryer skirt base ring had cutouts to fit around RPV support lugs, previous design had full length channels. 2) New dryer has two dryer guide slots at top and bottom of skirt vs: full-length channel in old design. **Root Cause**	Note: The basis for cause determination is similar for CF1a, & CF2b and are combined below: • Root cause supporting analysis concluded that the skirt region cracking would not have <u>initiated</u> had the Q2P03 dryer lift event not occurred. • Lift event resulted from changes in dryer installation hardware, not from personnel errors during dryer removal. • Tolerances between the dryer guide rod slots & guide rods allows for rotational movement of dryer resulting in skirt base plate cutouts not aligned with RPV support lugs. • Tolerance in guide components was further degraded by ovality issue. See Evaluation of Lifting Event Causal Factors CF1a, CF1b (section after this table) for more details on basis.
Event 1: Crack & deformation of dryer base plate and skirt identified in Q2R18.	CF1b. Lift Event - Fabrication: Ovality Results in Looser Installation Clearances - Distortion/ovality of dryer base plate further degraded alignment control provided by dryer guide slots. **Root Cause**	
Event 1: Crack & deformation of dryer base plate and skirt identified in	CF2: Disposition of damage from Q2P03 lift event concluded "use as is". GE FDDR, and site review concluded:	• FDDR accepted condition as-is but did not fully evaluate the material effects of the damage (focus on fit issues). • Assumed damage occurred in low stress

Problem Statement	Cause (describe the cause and identify whether it is a root cause or contributing cause)	Basis for Cause Determination
Q2R18.	• Modify base ring for separator guide rods • Run for 1 cycle • Repair/modify base ring for RPV Lugs in Q2R18 **Contributing Cause**	regions. • Inspections limited to visual & PT in the outside diameter areas. No detailed inspection of inside diameter. • Since follow-up analysis in this RCA did not identify an exact initiation mechanism for the cracking, a more detailed analysis during Q2P03 is unlikely to have changed the outcome. (For this reason, this issue is considered a contributing cause rather than a root cause). • Retained as a contributing cause because of small possibility that more detailed inspections could have detected cracks in the skirt or base plate, specifically on inner diameter areas. See "CF2: Disposition of Lifting Event Prior to Start-up from Q2P03" (Second section after this table) for more details on basis.
Event 1: Crack & deformation of dryer base plate and skirt identified in Q2R18.	CF3: Analysis – Operating Cycle Impacts **Contributing Cause**	• Operating pressure oscillation loads from MSL acoustics resulted in skirt base ring stresses that when combined with the reduced fatigue endurance caused by the plastic deformation from the lift event, was adequate to initiate and propagate cracking. • Considered a causal factor in crack initiation and propagation but not a root cause because analysis has concluded that the operating loads are not sufficient to initiate cracking on their own. • Att. 4 of this RCA presents a comparison of the U-2 pressure sensor data with the areas that experienced damage, which supports the conclusion that operating cycle impacts were not initiating factors or root causes to this event.
Event 2: Crack found in vane bank of "E" bank	CF4 - Cracking in Gusset 19 of Vane Bank "E" End Plate Near the 320° Location - most	• The basis for the cause determination is photographic observation by the root cause team and GE's evaluation

Problem Statement	Cause (describe the cause and identify whether it is a root cause or contributing cause)	Basis for Cause Determination
near 320 ° azimuth	probably due to assembly, and residual welding stresses, minimal weld thickness, proximity to a weld-stop (stress riser) and the presence of operating vibration loads **Root Cause**	(Reference 17). • The "Lift Event" was rejected as a causal factor for this event using a detailed stress analysis (Reference 36)
Event 3: Latch Box Crack at 220° azimuth	CF5 - Cracking in the 220° Latch Box – Per Ref. 18, the most likely cause of the cracking is fatigue cracking, the presence of a weld end discontinuity and likely high weld residual stress at the corner location. **Root Cause**	• The basis for the cause determination is the analysis and evaluation discussed in Reference 18, which concludes that the most likely cause of the cracking is the presence of a weld end discontinuity and likely high weld residual stress at the corner location. • The "Lift Event" was rejected as a causal factor for this event using a detailed stress analysis (Reference 36)

B. Discussion of the Basis for Cause Determination for Three RCA Events.

Event 1: Crack & deformation of dryer base plate and skirt.

1. CF1a, CF1b: – Lifting Event Causal Factors

A. Lifting Event: The May 2005 "Lifting Event" where the dryer was damaged from impact of the skirt base ring with the RPV lugs was a causal factor that contributed to the dryer cracks discovered in Q2R18. An apparent cause evaluation (ACE) was completed and approved in May 2005. This RCA reviewed this ACE and determined it to be an appropriate starting point for further analysis to determine why the event occurred.

The ACE (AR 334383) concluded:

> "Two apparent causes were identified for this ACE. First, lack of clearance between the Dryer base ring plate and the Separator guide rods resulted in damage to the ring plate and shifting of the Dryer that caused minor damage to two of the seismic support blocks. Second, excessive clearance between the Dryer guide rods and the Dryer (guide slots) allowed the Dryer to move enough that the close tolerance notches in the Dryer skirt base ring plate no longer aligned with the RPV dryer hold-down lugs. This allowed the ring plate to catch on the underside of the lugs and result in deformation of the ring plate in three areas."

This RCA considers the lack of clearance between the dryer skirt base ring and the separator guide rods to be an initiating event, but not a causal factor because the dryer is designed to be installed and removed as many times as needed to support plant operations. The interference with the separator guide rod was the reason for dryer removal in this case, but not the reason for the lift event. Therefore the next level of "Why" focused on the excessive clearance with the guide rods, and the close tolerances between the skirt base ring notches and the RPV lugs.

This RCA did consider the possibility that the cause of the impact was related to human performance issues with the crew removing the Dryer in Q2P03. This consideration arose from the fact that the U-2 Dryer was installed without damage twice during Q2P03, and removed once during Q2R18. (The Q2R18 removal was under the same configuration and close tolerances as Q2P03 since the modifications to improve this condition had not been completed yet). Information from interviews with personnel involved in the successful moves of the U-2 dryer, support a position that while the dryer can physically be removed under the configuration existing in Q2P03, the tolerances are such that an unacceptable risk of impact exists even with a reasonable measure of care. This information coupled with the results of the previously approved ACE led to a conclusion that the causal factors of the lift event were more related to the hardware clearance issues than crew human performance. Therefore the RCA pursued a "Cause and Effect Analysis" on the changes to design of the dryer installation hardware which resulted in the increased clearance with the guide rods, and the close tolerances between the skirt base ring notches and the RPV lugs noted in the ACE.

Cause & Effects Analysis – Design Changes to Dryer Installation Hardware (CF1a)

1. What were the changes?

Dryer Guide Device Clearance: The previous dryer had two guide channels that ran the outside length of the dryer. Once the channel was engaged onto the RPV dryer guide rods, little movement occurred as the dryer was installed into the RPV. Similarly, these full-length channels allowed for less movement when the dryer was removed, when compared to the new dryer design that uses dryer guide slots at the top and bottom of the Dryer Skirt. On the replacement steam dryer there are only 4 points of contact between the dryer and guide rods: - two at 0 and 180° on the base ring, and: -two at 0 and 180° on the mid-support ring. When the mid-support ring is not engaged with the dryer guide rods (i.e, the support ring is higher than the top of the upper dryer guide rod brackets), there are only 2 points of contact between the dryer and guide rods, at 0 and 180° on the base plate. Stated another way, only when the dryer base plate is 2" or more below the bottom of the RPV dryer support bracket (vessel lugs) will there be 4 points of contact. Thus, there are only 2 points of contact between the dryer and guide rods any time the dryer base plate is at the same elevation as the RPV dryer support brackets (vessel lugs). The dryer is therefore much less constrained in terms of the dryer/guide rod interface in the replacement design than it was in the original design, especially when the dryer base plate is at the same elevation as the RPV dryer support brackets (vessel lugs).

Skirt Base Ring Cutouts for RPV Support Lugs: The previous dryer used a channel mechanism to allow the dryer skirt to pass along the 4 RPV lugs. The new dryer design had cutouts at the skirt base ring that were nominally 4 inches wide to fit around a RPV

lug that is 3 inches wide. This allowed a one-inch margin (one half inch on each side) to install the dryer onto the RPV lugs.

2. Why were the changes made?

The new dryer installation project was completed to address past experiences with structural damage to the old dryer during operation at Extended Power Uprate (EPU) conditions. The new dryer was an original equipment manufacturer (OEM) replacement of a more structurally robust designed dryer. The reason the design was changed from full-length channels was to accommodate a change to relocate the drain channels from the inside of the dryer skirt to the outside of the dryer skirt. Since the OD of the dryer had to remain the same diameter so as to be able to fit in the vessel, the skirt diameter was reduced to make room for the drain channels on the outside of the skirt. The full-length guide rod channels that were previously an integral part of the skirt thus could no longer remain integral to the skirt. It was decided to not incorporate the full-length guide rod channels into the replacement dryer design and instead use the 4 points of contact design so as to minimize the weight increase of the replacement dryer. (As the dryer is made more structurally robust, the weight increases as heavier material is used, and the increased weight had to be maintained within the structural capabilities of the RPV dryer support lugs.)

3. Why were the potential adverse consequences to the installation hardware changes missed?

> <u>Barrier Analysis</u>: The barriers expected to prevent adverse consequences from this design change included:
>
> a. A design product provided by the vendor designer where all potential adverse consequences associated with the change are addressed.
>
> b. Review and approval of the vendor provided product by Exelon design personnel using the process defined in CC-AA-10, “Configuration Control Process Description” and other associated procedures.
>
> c. Review of the design product by the end user (in this case Reactor Services) to determine if there any adverse installation concerns created by the design change.

In this case the vendor providing the design product is GE, who was also the Original Equipment Manufacturer (OEM). Interviews with a GE design person indicated the use of slots versus channels was considered an acceptable option based on trouble free application of this design in the dryers of more recent vintages of GE BWR’s. The GE designer believes that the use of slots in the new dryer was, and is acceptable, but in the case the QC2 dryer, was further degraded by the “ovality” fabrication issue.

Site design personnel review efforts were focused on structural factors, the instrumentation unique to this particular dryer, and similar technical items. The design engineers have little “hands on” experience with dryer installation. The Exelon Engineering Change (EC) review process accounts for this gap in hands on experience by using cross discipline reviews from personnel who do have this experience. In this design change, the end user, Reactor Services completed Att. 10F of CC-AA-102,

“Configuration Change Review Checklist for Use by Other Departments” indicating they understood and accepted the impact of this change on their department. Follow-up interviews with GE and Exelon Reactor Services personnel indicated that the change in installation hardware, and resulting closer installation tolerances, was a well-known issue. These personnel believed the change could be accommodated with additional care during installation. One example of this additional care was that during the initial installation, personnel were in the reactor refueling cavity bulkhead to closely watch the lowering load. This option was known to not be available in future Dryer installations since they are performed under water after the dryer has been exposed to operating conditions that elevate the radiological dose rates. The intent was to determine if the dryer could be successfully installed despite these tighter tolerances, and pursue modifications if needed for future installations.

This evaluation concluded that for these changes to the dryer installation hardware:

- OEM (GE) personnel had provided the design for use in the Exelon EC process.
- The design change process had been followed as specified in the governing procedures.
- Appropriate “end user” personnel (in this case Reactor Services) had been included in the design change review.
- These Reactor Services personnel had significant experience.

Despite these factors, unanticipated negative consequences occurred, that were associated with these design changes.

This evaluation pursued the organizational and programmatic factors that had influenced these negative results. At this point in this RCA, it was known that causal factors associated with this event shared some similarities with those of another recently approved RCA, an investigation of Electromatic Relief Valve Solenoid Failures (Ref. 38). A review of the corrective actions associated with the ERV RCA identified that several of these actions would be well positioned to address the weaknesses identified in this RCA.

Additionally, a second RCA “QC2 Replacement Steam Dryer Impact on Fuel Analysis Results” (Ref. 37) was reviewed. This RCA was completed in May 2005 when it was determined that the replacement dryers would not meet the design requirement for differential pressure (dP). This RCA contained corrective actions intended to reduce the probability of negative consequences associated with major design changes and projects.

Corrective actions will be needed to prevent recurrence of the dryer lifting event specific to the RCA (since dryer removal will occur each future refueling cycle). Actions will also be needed to address the organizational and programmatic issues that allowed the negative design change consequences to occur. The subsequent section, “IX. Corrective Actions to Prevent Recurrence”, and “X. Corrective Actions”, presents corrective actions associated with the lifting event. Section “XII. Programmatic/ Organizational Issues” details the corrective actions to address the more global concern related to preventing unanticipated negative outcomes of design changes.

CF1b: Cause & Effects Analysis – Fabrication Induced Ovality

The additional movement and reduced tolerances allowed by new installation hardware in the QC U-2 dryer was further degraded by a fabrication problem which resulted in the skirt being approximately 2 inches out of round ("ovality issue"). The orientation of the out of round position further allowed additional movement between the dryer guide slots and the RPV guide rods. The concern related to the ovality impacting installation clearances was recognized. The DDR (Ref. 7) resolving the ovality issue noted – "Dimensional analysis of the as-built hardware indicates that the dryer will fit in the vessel. Clearances normally available have been compromised, so additional guidance constraints will be placed in the lower guide block, to limit misalignment and assist in installation." The additional guidance constraints were in fact installed as documented in Ref. 9. These constraints helped reduce potential movement between the dryer and the vessel wall, but did not have any impact on lateral movement. It is believed that this lateral movement contributed to the "lift event" by allowing the dryer to rotate about one inch due to the slop between the dryer guide slots rods and the RPV dryer guide rods. This minimal rotation contributed to the dryer skirt base cutouts for the RPV lugs, being out of alignment with the RPV lugs, which allowed for the skirt base plate to impact on the bottom of the reactor lugs as the dryer was being lifted out of the reactor vessel.

Note: Att. 7 contains more detailed descriptions and pictures regarding the movement of and damage to the U-2 Dryer during the Lifting Event.

CF2: Disposition of Lifting Event Prior to Start-up from Q2P03

Given that this RCA concludes that damage from the May 2005 (Q2P03) lifting event was a primary causal factor for the cracking identified during Q2R18 inspections, and the damage from this event was a known issue, it is logical to conclude that this disposition was a "missed opportunity" to prevent the dryer skirt cracking. This section describes the evaluation performed for potential causal factors associated with the reviews completed after the lifting event that occurred. The table below describes the major reviews and milestones that occurred, during and shortly after Q2P03.

Q2P03 Lift Event Follow-up Decision Timeline

Date	Time	Event
5/11/05	2300 (approx.)	Lift event occurred
05/12/05	0156	OCC notified
05/12/05	0700	Prompt Investigation Initiated (Ref. 4)
05/12/05	NA	Exelon comment matrix for review of FDDR RMCN 06243 notes need to assess: 1. "cold work and/or residual stress in the weld." 2. "magnitude of the plastic strain to determine the

		potential susceptibility."
05/13/05	~0700 (prior to install)	Liquid Penetrant testing performed on selected damaged and/or repaired areas of Dryer (Ref. 1)
05/13/05	0710	Dryer Repaired, Modified and set into the RPV
05/13/05	0900 (assumed)	Prompt Approved by MRC.
05/13/05	NA	FDDR RMCN06245 Issued by GE to Resolve Lift Event Damage. Implemented under Exelon WO 742798-1 (Ref. 8)
05/14/05	NA	PORC approval of EC 351168- Rev.2– incorporating FDDR RMCN 06243 into the Exelon EC process.
05/16/05	0345	U-2 Start-Up from Q2P03
05/24/05	NA	Exelon Corporation concurrence letter for FDDR RMCN 06243 issued. (Ref. 30)
05/25/05	NA	ACE on Lifting Event Approved by MRC (Ref. 2)

This RCA reached the following conclusions regarding the Q2P03 assessments of the lifting event:

1. There was no evidence of any formal review (HU-AA-1212, or similar process) to specify what areas of the Dryer areas were to be inspected after the lift event. Non-destructive examination (NDE) personnel performed liquid penetrant examinations of damaged and or repaired areas at the direction of GE refuel floor supervision. (Ref. 1) These examinations included outside diameter areas, no inner diameter areas were inspected.
2. Only anecdotal evidence of evaluation of cold work or elastic strain impacts could be found. Personnel who were involved in the review of the GE FDDR (Ref. 8) recalled discussions of these topics, and conclusions that the ductile nature of stainless steel, and low stresses in the skirt/baseplate regions, made future problems unlikely. This RCA found no documented, formally reviewed structural analysis reports or evaluations completed prior to restart from Q2P03.

Formal structural analyses (Ref. 29&36), and metallurgical evaluations (Ref. 19), were completed as part of this RCA. Because these analyses could not identify the exact initiation mechanism of cracking, a detailed analysis during Q2P03 is unlikely to have changed the outcome, (formal analysis would have concluded the unit could be restarted without major replacement of dryer skirt components). For this reason, the weaknesses associated with the Q2P03 lifting event disposition are not considered a root cause to this event. The weaknesses are retained as a contributing cause because more detailed

inspections could have detected cracks in the skirt or base plate, specifically on the inner diameter areas. In addition, more detailed inspections in the inner diameter regions would have better identified the magnitude of the deformation, which may have resulted in a different conclusion of corrective actions needed.

Event 2: Crack found in vane bank of "E" bank near 320° azimuth

The basis for the determination of minimal weld thickness, proximity to a weld-stop (stress riser) is photographic observation by the Quad Cities root cause team. Reference 17, Figure 1, last image, shows that the weld buildup is smaller than adjacent portions of the weld and also shows the weld-stop. Additionally, hood assembly and weld residual stresses may have been produced due to the alignment of 6 vane panels in the "E" hood and the weld shrinkage when welding the hood panels and gussets to the vane panel end plates and trough. (This results from differential thermal expansion and contraction that occur from the temperature difference between the weld bead and the cooler base metal.) These factors are postulated to, in the presence of operating vibration loads, have initiated the crack.

Event 3: Latch Box Crack at 220° azimuth

The basis for the cause determination is Reference 18, which notes "that the crack appeared to have initiated at the corner where one latch box to skirt panel weld either began or ended. Also, the weld end appears to have a discontinuity in the form of a small crater. It is well known that the beginning or end of a weld bead could have some discontinuities that could serve as a fatigue crack initiation site. The other contributing factor could be the corner location where the two welds are meeting that could produce high fit up stress at that location. The presence of high weld residual stress could lower the fatigue stress threshold and may result in the initiation of a fatigue crack. Therefore, it is concluded that the most likely cause of the cracking is the presence of weld end discontinuity and likely high weld residual stress at corner location."

C. Discussion of Evaluation of "Other Conditions"

Conditions in the table below were determined to not be CF's for this event, but warrant additional discussion for clarity purposes, and to ensure priority issues are resolved even if they did not contribute to these events. The table summarizes these events. For some of the more complex issues, a more detailed discussion appears at the end of the table.

Condition Description	Issues, Basis, Resolution
C.1: Crane load cell unavailable.	• Effect of not having load cell display available was not effectively resolved prior to the lifting evolution. • RCA inconclusive if load cell could have prevented event but there are clear opportunities to enhance the use of this barrier in future. • CA's specified in "Other" Section (More detailed discussion appears at the end of this table.)
C.2: Finite Element Model Did Not Include Detail For New Dryer Design Below Water Line	• RCA determined extensive issues in configuration control between the as built replacement dryers and the GE analysis model (one example - base plate cut-outs were not included in analysis model). • Structural analysis associated with the RCA determined that this lack of configuration control did not contribute significantly to this event (Ref. 29) (More detailed discussion appears at the end of this table.)
C.3: Metal Stress Inducing Factors - Design: Used super element model for new dryer design.	• Base plate and skirt gusset load concentration not modeled. • Model assumed full penetration welds for the base plate to skirt, while the design and fabrication installed partial penetration welds. • Analysis model did not include cutouts in the skirt base plate. • Structural analysis associated with the RCA determined that this lack of detailed analysis did not contribute significantly to this event (Ref. 29)
C.4. Metal Stress Inducing Factors - Fabrication: Distortion/ ovality of dryer base plate	• Stress induced in the dryer skirt & skirt base plate due to two halves of dryer being force fit together, resulting in ovality of the skirt and skirt base plate. • Stress contribution to skirt cracking would be limited to elastic distortion of the base ring. • Impact of residual stresses was not specifically

Condition Description	Issues, Basis, Resolution
	analyzed in Q2P03 because skirt is a low stress region. • A follow-up evaluation associated with this RCA (Ref. 33) was completed and concluded that the small plastic strain and residual stresses directly attributable to the ovality issue did not contribute to the observed cracking. (More detailed discussion appears at the end of this table.)
C.5: Structural – Fabrication: Welding of base plate to dryer skirt showed lack of penetration.	• Dryer material sample showed a lack of weld penetration at skirt and base plate connection • Metallugical Analysis completed for this RCA concluded that the lack of penetration was not completely unexpected for this type of weld. This analysis also concluded that this issue was not a causal factor for the observed cracking. • More detailed discussion and excerpts of Ref. 19, the GE Metallurgical Analysis were included in the previous “Analysis” section of this report and are not repeated here.
C.6: Structural – Fabrication: Use of halide containing weld wire coupled with cracking allowed SCC initiation.	• Dryer material samples from both the 140° and 220° regions indicated a presence of TGSCC. • Metallurgical Analysis completed for this RCA concluded that the TGSCC was not an initiating factor for the observed fatigue cracking. TGSCC in the 140° region was more extensive than the 220° region. It is believed this condition was caused by the water introduced to the area after the fatigue cracking occurred in the 140° area. • More detailed discussion and excerpts of Ref. 19, the GE Metallurgical Analysis were included in the previous “Analysis” section of this report and are not repeated here.

C.1: Crane Load Cell Display Unavailable Allowing Excess Forces On Dryer

The Reactor Building Overhead Crane (RBOC) is provided with a load cell that will sense the weight on the crane hook with an output signal to a crane power interlock switch. The set point of this switch is 250,000 lbs (125 ton), equal to the rated crane capacity. The load cell signal also provides input to a digital readout, which if properly calibrated, will provide the accurate weight of a lifted load. There is a primary readout on the control unit located on the crane trolley, which cannot be viewed remotely. There is, however, a secondary display that can be viewed from the crane operator's cab as well as the refueling floor.

During the review of the Steam Dryer lift event on May 12, 2005 (Q2P03) it was determined that this lift was performed with a non-functioning digital readout display from the load cell (secondary display). (Note: The 125-ton crane power interlock was functional, only the display function was inoperable). Procedure QCMM 5800-05 "Reactor Building Overhead Crane Utilization", Step 3.3.1 states:

> "if the … readout does not display any digits, **WRITE** a Work Request for repair. This does **<u>not</u>** render it inoperable **if** all view angles around the lift can be verified to ensure **<u>no</u>** interferences are encountered."

There is no evidence that a Work Request (WR) or an Issue Report (IR) was initiated at this time, however, a prior request was initiated on 4/21/05 (AR# 327007). This request (WR# 176082) was closed to WO# 805641-02 for calibration of the load cell and repair of the digital readout, which was completed on 5/16/05, approximately 4 days after the dryer lift event.

Per discussion with the contracted crane maintenance vendor, it is understood that the digital readout will provide accurate indication of a slight change in load (≈ 200 lbs) on the crane hook, which would be indicative of a load hang-up. It is also understood that monitoring of the load could easily be accomplished by using a dedicated person to watch the display for any increase in load indication. This person would be located near the signalman, thereby being within sight of the crane operator without distracting either the signalman or the crane operator from their respective load handling responsibilities. The person monitoring the load display can terminate the lift at any time a change in load is observed.

Based on the speed of the hoist in slow speed (< 2ft/min.) and reasonable reaction times by the load monitor and the operator, it is expected that the lift could be suspended with a minimal amount of load on the contact points due to hang-up of the load.

The ACE conducted at the time of the event (Ref. 2) concluded that since the rigging is a "metal to metal" contact throughout, any load cell deviations would be instantaneous and would not allow for operator action to prevent possible consequences …" This RCA, however concludes that had the load cell secondary readout been functioning and a dedicated person assigned to monitor and halt operation of the crane at a predefined criteria the damage could have been minimized.

The finite element analysis conducted to estimate the force necessary to permanently deform the skirt base ring ¾ of an inch would be around 47,000 lbs. Since the load cell can sense load differences as small as 200 lbs., and the the skirt base plate would deflect

in an elastic manner at some lesser force before it would plastically deform to the ¾ inch deflection, the lift could have been stopped prior to any permanent deflection.

During interviews, it was evident that the lack of a functioning load cell display had become an expected norm and the procedure had been written to allow the use of the RBOC without the load cell functional. It is also reasonable to conclude that with the heightened sensitivity to the dryer clearances due to the changes in design and to fabrication problems (ovality), that more emphasis should have been placed on the operation of the load cell.

C.2 Finite Element Model Did Not Include Adequate Detail For New Dryer Design

A potential failure mode that was identified and subsequently rejected, was that the finite element model for the dryer could be inadequate for the new dryer design. If this allowed an inadequate margin condition to exist without the model showing the problem, then a design inadequacy would go undetected.

The evidence indicates that the cracks occurred primarily because of residual stresses associated with the dryer lift / impact event. Normally, the dryer modeling would not be used to ensure margin to mis-handling events, except possibly in very low dimensional clearance margin conditions such as this (where a user error is likely).

During RCA, several vulnerabilities were discovered, which the dryer model was not detailed enough to detect. One example is that the gussets placed adjacent to the notches in the base plate, could cause ring deflection(s) to be transferred to the skirt panels, allowing a cyclic loading. A second example was that the cutouts for the RPV lugs were not modeled. This prevented the opportunity to detect local stress conditions that may be present in the skirt or base ring in the vicinity of the cutout. Since the model did not detail these conditions, additional detailed finite element modeling was needed to better evaluate this possible cause.

Additional detailed finite element analysis (FEA) completed in a GE report titled "Quad Cities Unit 2 Replacement Steam Dryer Analysis, Detailed Stress Analysis of Skirt Base Plate Cutouts and Gussets." (Ref. 29) concluded that:

> "The analysis results show that the effect of the cutout on the skirt response is insignificant and the original stress analysis without this detail is adequate. In addition, the fatigue stress levels at the cutout in the base ring for all configurations (original, as found, and repair design) are very low compared with the endurance limit of 13.6 ksi …"
>
> "The inelastic analysis results show that the lug/base plate impact resulted in significant levels of irreversible plastic deformation that could have contributed to crack initiation due to a combination of residual stress inherent in plastically deformed structures and flow-induced vibratory stresses."

The conclusions of this analysis supports elimination of lack of detail in the FEA as a potential cause, and supports the RCA position that stresses from the lifting event were causal factors in Event 1.

C.4. Metal Stress Inducing Factors - Distortion/ovality of dryer base plate (Ref 33)

GE completed additional analysis of this condition in support of this RCA. Excerpts of this analysis appear below, which support a position that stresses from ring ovality did not contribute to the events in this RCA:

> Given the sequence of events, it is reasonable to conclude, as stated in the DDR disposition, that the distortion of the base ring was a consequence of welding the additional supports into the upper steam dryer structure. Weld shrinkage between the dryer banks could have transmitted a load into the skirt tending to make the structure, including the base ring, slightly oval. However, when considering the potential effects of this distortion relative to the failure observed at the 140º location, there are two important points. First, it should be recognized that, at 247 inches diameter and only one inch thick, the base ring is a relatively flexible component. Two inches deviation in a 247 inch diameter is only about 0.8% diametral distortion, which represents neither significant working of the material nor residual stress. In fact, a large fraction of this projected maximum distortion of 0.8% is elastic rather than plastic deformation. Circumferential strain, which would be more indicative of permanent plastic deformation, is essentially a net of zero since the diameter is approximately the same amount undersize 90 degrees from the oversize points. In any event BWRVIP-84* allows up to 2.5% permanent plastic strain for the purposes of straightening stainless steel components. The plastic strain attributable to the diametral distortion is much less than this limit.
>
> The second consideration is that the failure occurred at the 140º azimuth, which is approximately midway between the minimum and maximum diameters. Therefore, the failure occurred near a neutral point where the diametral distortion and stress would be minimal. However, it is recognized that in this region, especially in the cutout in the base ring, the balance between the oversize diameter and the undersize diameter would tend to produce some amount of bending of the ring. This produced some incremental amount of torsional load in the cutout region that would be additive to the overall stress applied in the failure location. Nevertheless, it is concluded the small plastic strain and residual stress directly attributable to the observed diametral deviation had no role in the failure.

VI. Extent of Condition:

Cause being addressed	Extent of Condition Review
CF1a - Guide Channels Not Used in New Dryer Design	The Quad Cities Unit 1 and Dresden Units 2 and 3 replacement steam dryers also do not use channels. The modification to the Quad Cities Unit 2 (QC2) dryer of wider base ring slots has been incorporated into the design of these three dryers and the attention required during lift to the possibility of "hanging up" the dryer base ring on the dryer (RPV) support lugs has been communicated to Dresden, and will be communicated to the industry through the OPEX process.
CF1b – Ovality Results in Looser Installation Clearances	The Quad Cities Unit 1 and Dresden Units 2 and 3 replacement steam dryers were/are constructed in two halves, shipped and welded together at J. T. Cullen. Measurements showed that the dryer skirt was oval following the welding. The looseness caused by the ovality is postulated to be an element in the dryer removal event. The lessons learned regarding rigging and welding to prevent the dryer from becoming oval have been incorporated in the fabrication of these three dryers.
CF2: Analysis & Inspections of Damage from Q2P03 lift event concluded "use as is". GE FDDR, and site review concluded: • Modify base ring for separator guide rods • Run for 1 cycle • Repair/modify base ring for RPV Lugs in Q2R18	The evaluations, examinations and analyses performed immediately after the dryer lift event in Q2P03 did not have sufficient rigor. As noted in the Evaluation section, it is likely that these weaknesses, especially in the analysis area, would not have changed the outcome of the event, however there is some finite possibility of a missed opportunity to prevent this event from this CF. The Programmatic/ Organizational issues associated with this CF are unlikely to be repeated in dryer components, given the limited population of similar dryers, but there are extent of condition concerns related to other RCA reports reviewed as part of this analysis. Several corrective actions recently initiated in these other RCA are well aligned with this CF, and should be expected to have a positive impact on this concern. These items will be addressed in more detail in the subsequent Corrective Actions section of this report.
CF3 - Data Collection From Instrumented Dryer Acoustic Loading @ 150 Hz	Vibrations are present to a degree in all the Units. They are measured and used in the analyses or compared to analyzed levels. Consequently this should not be an issue for other stations / units.
CF4 – Issue 2: Bank "E" End Plate Cracking	Section 1 of Reference 19 reads in part: "Following the discovery of cracking <in Gusset 19>, all remaining locations were inspected. All of the other gussets were found to be acceptable with no evidence of cracking." Therefore, it is concluded that this is an isolated incident.
CF5 – Issue 3: Steam Dryer Latch Box Cracking	Latch box protectors have been installed under EC 351167, Rev. 1 for Unit 1 and EC 348286, Rev. 0 for Unit 2. No other latch boxes were found cracked during these installations.

VII. Risk Assessment:

Plant-specific risk consequence	Basis for Determination
Industrial Safety – Minimal Risk	Although the load cell display was not functioning, the circuitry does not allow a lift of over 125 tons nominal. Given the safety factor of 5 required for the crane and other lifting members, the members would have been able to withstand the load up to the crane lift cutout without failing.
Nuclear Safety – Minimal Risk	Dryer component cracking could result in lost parts. Various lost parts analyses have been performed in the past (most recently for a steam dryer 94 lb. lifting lug for Unit 1 and a steam dryer 9" x 6" plate for Unit 2). The most significant consequence has been determined to be a risk to production. No risks to nuclear safety have been found. Additionally, the Quad Cities Risk Management Expert and the Corporate Model Owner have reviewed the Steam Dryer Gusset Cracking Condition (IR 473034), the Steam Dryer Skirt Cracking Condition (IR 472321) and GE-NE-0000-0052-6385-R0, Lost Parts Analysis for Dryer Lifting Lug and Dryer Skirt Panel Unit 1, to provide support for the PRA modeling. Basically, the risk assessment review found the risk increase associated with these conditions to be minimal and not risk significant, as documented in Reference 26.
Regulatory Impact – Minimal Risk	There is Regulatory Impact from the standpoint that the Station has assured the Regulator that a more robust dryer has been installed, that the loading on the dryer is understood, the dryer has been shown analytically to be able to withstand the loading and that there should be no cracking of the dryer. However, dryer cracking was found during Q2R18, resulting in a decrease in the credibility of the Station with the Regulator. Note that the dryers are non-safety related, seismically designed. Due to the location of the cracking and the measure strain hardening of the dryer material, the cause of the cracking is judged to be the lift event. Inspection of the Unit 1 dryer during Q1M19 determined that this undamaged dryer did not have cracking comparable to the Unit 2 dryer supporting the conclusion that the dryers were designed adequate to withstand the loads (minus a lifting event) as committed to the Regulators.
Production / Cost – Minimal Risk	Based on the following, there is minimal likelihood of recurrence of this dryer cracking event: a. GE's root cause analysis of the dryer 140° skirt cracking, Reference 21, identifies the lift event and consequent material strain hardening as the probable cause, b. Dryer analysis using measured vibration loads and confirmed using strain gages shows that the dryer is able to withstand the operating loadings and c. The Unit 1 dryer (without a lift event) as-found condition following approximately 10 months of operation, about ½ that time at EPU power levels, was acceptable and as expected.

VIII. Previous Events:

Previous Events	Previous Event Review
None	Many OPEX reports were found that identified cracking and most of them identified flow induced vibration or undersized welds as the cause. No case was found of dryer damage due to or during lifting of the dryer.

IX. Corrective Actions to Prevent Recurrence (CAPRs):

Root Cause Being Addressed	Corrective Action to Prevent Recurrence (CAPR)	Owner	Due Date
CF1a - Guide Channels Not Used in New Dryer Design	CAPR 1 - Modifications to improve installation hardware on U-2 Dryer [i.e., increased lead-in on dryer mounting blocks, install lug spacer blocks, etc.] - EC 348286, Rev. 1 CAPR 2 - Modifications to improve installation hardware on U-1 Dryer {i.e., enlarging base ring RPV lug cutouts) – EC 351167, Rev. 1	Completed Completed	Completed during Q2R18 Completed during Q1R18
CF1b – Ovality Results in Looser Installation Clearances	CAPR 3 - Modifications to improve installation hardware on U-2 Dryer [i.e., guide rod block extension] - EC 348286, Rev. 1	Completed	Completed during Q2R18
CF4- Vane Bank “E” End Plate crack, caused by little metal between end plates, and proximity to a weld transition (stress riser).	CAPR 4 - Analysis to justify leave “as is” position (Ref. 17).	Completed	Completed during Q2R18
CF5- Latch Box cracking at 220°, caused by high residual weld stress from weld end discontinuity and corner location.	CAPR 5 - Repair to this area. - EC 348286, Rev. 1	Completed	Completed during Q2R18

X. Corrective Actions:

Cause Being Addressed	Corrective Action (CA) or Action Item (ACIT)	Owner	Due Date
CF2: Analysis & Inspections of Damage from Q2P03 lift event concluded "use as is". (Lack of rigor in analysis, limited follow-up inspections.)	This RCA concluded that recently approved corrective actions for a RCA related to "Quad Cities Electromatic Relief Valve Solenoid Actuator Failures…" (Ref. 38) are well aligned with CF2 for this RCA, and are appropriate corrective actions for this RCA. The corrective actions are comprehensive, and will establish revised programmatic controls to ensure additional rigor is applied to situations similar to the Lifting Event. These corrective actions are provided as ATT. 9 to this RCA.	See ATT. 9	See Att. 9
CF3 – Operating Loads on Dryers During EPU Conditions	Unit 2 - Install Acoustic Side Branches (ASBs) to reduce vibration levels - EC 359004, Rev. 1	Complete	Completed during Q2R18
	Unit 1 - Install Acoustic Side Branches (ASBs) to reduce vibration levels - EC 359006, Rev. 1	A8452DEM	AT 435858-37 due 05/26/2006

XI. Effectiveness Reviews (EFRs):

CAPR / CA being addressed	Effectiveness Review Action	Owner	Due Date
CAPR 1 & 3 - Modifications to improve installation hardware on U-2 Dryer [i.e., increased lead-in on dryer mounting blocks, install lug spacer blocks, etc.] - EC 348286, Rev. 1	Remove and re-install the U-2 replacement dryer during Q2R19. Verify that available clearances are acceptable to prevent damage during future dryer installation and removal activities. The U-2 dryer was modified with improved installation hardware in Q2R18. The U-2 Dryer is slightly different from U-1 due to the "ovality" issue. This action will validate the effectiveness of CAPR 1 & 3. AT 472321 - XX (est. after RCA approval)	Rx. services.	Q2R19 May 2008

CAPR 2 - Modifications to improve installation hardware on U-1 Dryer {i.e., enlarging base ring RPV lug cutouts) – EC 351167, Rev. 1	Remove and re-install the U-1 replacement dryer during Q1M19. The U-1 dryer was previously modified with improved installation hardware in May 2005. This action will validate effectiveness of CAPR 2 by demonstrating that the dryer can be removed and installed without damage.	Rx. services	Completed in Q1M19: No dryer removal or installation problems encountered.
Validates major RCA conclusions regarding cause of 3 cracking events in the U-2 Dryer. (CF's 1a & 1b- for Event 1, CF4 for Event 2, CF5 for Event 3)	Inspection of the U-1 replacement dryer during Q1M19 concluded: 1) U-1 does not exhibit the skirt-cracking present on U-2 during Q2R18 which supports the position of this RCA that the U-2 lifting event was the cause for the skirt cracking. 2) No evidence Vane Bank or Latch Box cracking which supports position that Events 1 & 2 of this RCA do not represent generic design weaknesses or operating cycle concerns for the replacement dryers.	Programs Engineering	Completed Q1M19: Confirmed no similar damage to U-1 Dryer (Ref. 39)
CAPR 4 - Analysis to justify leaving Vane Bank "E" cracking "as is" (Ref. 17).	Future inspections in Vane Bank "E" area during next U-2 outage to verify condition remains acceptable to leave as is. AT 472321 – XX (est. after RCA approval)	A8451NESPR	During Q2R19 [5/31/2008]
CAPR 5 - Repair to Latch Box cracking at 220° - EC 348286, Rev. 1	Future inspections in Latch Box area during next U-2 outage to verify repair completed in Q2R18 was successful in preventing future cracking. AT 472321 – XX (est. after RCA approval)	A8451NESPR	During Q2R19 [5/31/2008]

XII. Programmatic/Organizational Issues:

This RCA identified two programmatic/organizational issues:

A. The original disposition of the lifting event in Q2P03 (May 2005) lacked rigor, and was potentially a missed opportunity to prevent the dryer skirt cracking.

B. Multiple examples of unanticipated negative consequences from the replacement dryer design.

Item A, the original disposition of the lifting event, has been extensively discussed in previous sections of this RCA since it is considered a contributing cause to these events (CF2). As such, there is no need for additional clarifying discussion in this section. Item B, related to unanticipated negative consequences of the replacement dryer design change, will be discussed in more detail to provide specific examples and to clarify the impacts of this issue.

Both issues are included in the table at the end of this section, which summarizes the issue and associated corrective actions.

<u>Unanticipated Negative Design Consequences</u>:

This RCA noted several examples of negative consequences from the design of the replacement dryer. This includes:

1. Separator guide rod interference with the dryer skirt ring. This issue resulted when the replacement dryer design did not ensure that fit-up problems did not exist. This issue became an initiating factor for the lifting event**.**
2. The change in dryer installation hardware from full-length guide channels to guide slots and base ring cutouts was a causal factor (CF1a) for the lifting event. This issue resulted when the potential negative consequences of the design change were not identified despite completing the requirements of the design change process, and associated cross disciple reviews.
3. The initial response to the ovality issue included a modification to install guide rod spacer blocks (Ref. 9) to address clearance concerns. This initial modification was completed prior to dryer installation, but was insufficient to prevent the ovality problem from becoming a causal factor (CF1b) for the lifting event.
4. The replacement dryer differential pressure (dP) did not match the design specified value. This issue was the subject of a separate RCA - Ref. 37. The unexpectedly low dP of the replacement dryer dP had negative impacts of: a) Increased complexity and costs associated with fuel analysis for subsequent operating cycles, and b) Degraded moisture carryover performance from the new dryers.

The number of unanticipated negative consequences from the replacement dryer design clearly demonstrate a programmatic and organizational weakness. The consequences of these items clearly warrant corrective action.

As noted in the "Evaluation" section, the issue of unanticipated negative design consequences identified in this RCA shared some similarities with two other RCA's:

- Electromatic Relief Valve Solenoid Failures (Ref. 38).
- QC2 Replacement Steam Dryer Impact on Fuel Analysis Results" (Ref. 37)

A review of the corrective actions associated with these RCA's identified that several of the items in progress would be well positioned to address the issue identified in this RCA.

Attachment 9, section B., lists these corrective actions already tracked by AT's under Refs. 37 & 38.

In September of 2005 a Common Cause Analysis (CCA) was completed on modifications (AR 317566) which identified a need to improve the effectiveness of inter-departmental reviews associated with the design change process. Corrective actions associated with the CCA were implemented in fall 2005, so they would not have impacted the events of this RCA, which occurred in May 2005. A follow-up action is recommended to perform an effectiveness review of the CCA corrective action implementation to determine if they have been successful in improving the use of the inter-departmental reviews in identifying and avoiding unanticipated negative consequences of design changes.

Section B of the table below summarizes the intent of the actions in progress from the other RCA's and lists the actions to be tracked under this RCA.

Programmatic and Organizational Weaknesses	Corrective Action (CA) or Action Item (ACIT)	Owner	Due Date
Item A: Review & Disposition of Lifting Event Damage During Q2P03	As noted in the previous Corrective Actions section, this CF will be addressed by recently approved corrective actions associated with the ERV Actuator RCA. These actions are intended to improve the application of formal decision-making processes under conditions similar to the lift event in this RCA. Formal decision making processes will enhance the level of rigor. These actions are listed in Att. 9, Section A of this RCA.	See ATT. 9	See ATT. 9

Programmatic and Organizational Weaknesses	Corrective Action (CA) or Action Item (ACIT)	Owner	Due Date
Item B: Unanticipated Negative Design Consequences	Similar issues identified and tracked under other RCA's (Refs. 37 & 38) are listed in Att. 9. These CA's are expected to improve the effectiveness of inter-departmental reviews of design changes, and to improve the coordination of major modifications that become Exelon projects. New CA's specific to this RCA are listed below. 1. Quad Cities to implement Rev. 1 of HU-AA-1212, "Technical Task Risk/ Rigor Assessment…" which includes guidance on how to select what type of third-party review(s) are required. 2. Design Eng. to complete an effectiveness review (EFR) of the corrective actions (CA's) implemented from CCA 317566. The overall intent of this EFR is to determine if the CA's have improved the use of the inter-departmental reviews in identifying and avoiding unanticipated negative consequences of design changes. (An example directly from this RCA would be: More detailed Reactor Services review & challenge to ensure the design is usable for dryer installation activities.)	See ATT. 9 A8400PM – QDCDW AT 472321 – XX (ACIT) A8452 NESDP AT 472321 – XX (ACIT) (est. after RCA approval)	See ATT. 9 07/31/06 11/17/06

XIII. Other Issues:

Other Issues identified during investigation	Corrective Action (CA) or Action Item (ACIT)	Owner	Due Date
1. Crane load cell unavailable during Lifting Event	a. Evaluate methods to improve the use of the load cell as a method of early detection of load "hang up". This needs to include establishing expected load values, and abort criteria when pre-established thresholds are reached. These methods should be incorporated in to QCMM 5800-05, or other suitable	Rx. Services AT 472321 – XX (ACIT) (est. after RCA approval)	11/10/06

Other Issues identified during investigation	Corrective Action (CA) or Action Item (ACIT)	Owner	Due Date
	documents. These methods should also discuss appropriate contingencies if the load cell is unavailable, and suitable management review and approval levels for invoking these contingencies. Results of this evaluation should be presented to MRC for closure.		
2. Crane load cell unavailable during Lifting Event	b. Evaluate historical reliability of RB Overhead Crane Load cell display. Determine if actions for improving future reliability are warranted. Present results of this evaluation to PHC for closure.	Plant Engineering. AT 472321 – XX (ACIT) (est. after RCA approval)	09/29/06

XIV. Communications Plan: Preliminary NER and OPEX information has already been provided for communication within Exelon and the Nuclear Industry. Final communication actions are being tracked by the AT items below:

Lessons Learned to be Communicated	Communication Plan Action	Owner	Due Date
Provide NER to share lessons learned within Exelon	472321-09	A8430TP	06/01/06
Provide an OPEX to share lessons learned with the rest of the industry	472321-10	A8401OPEX	06/08/06

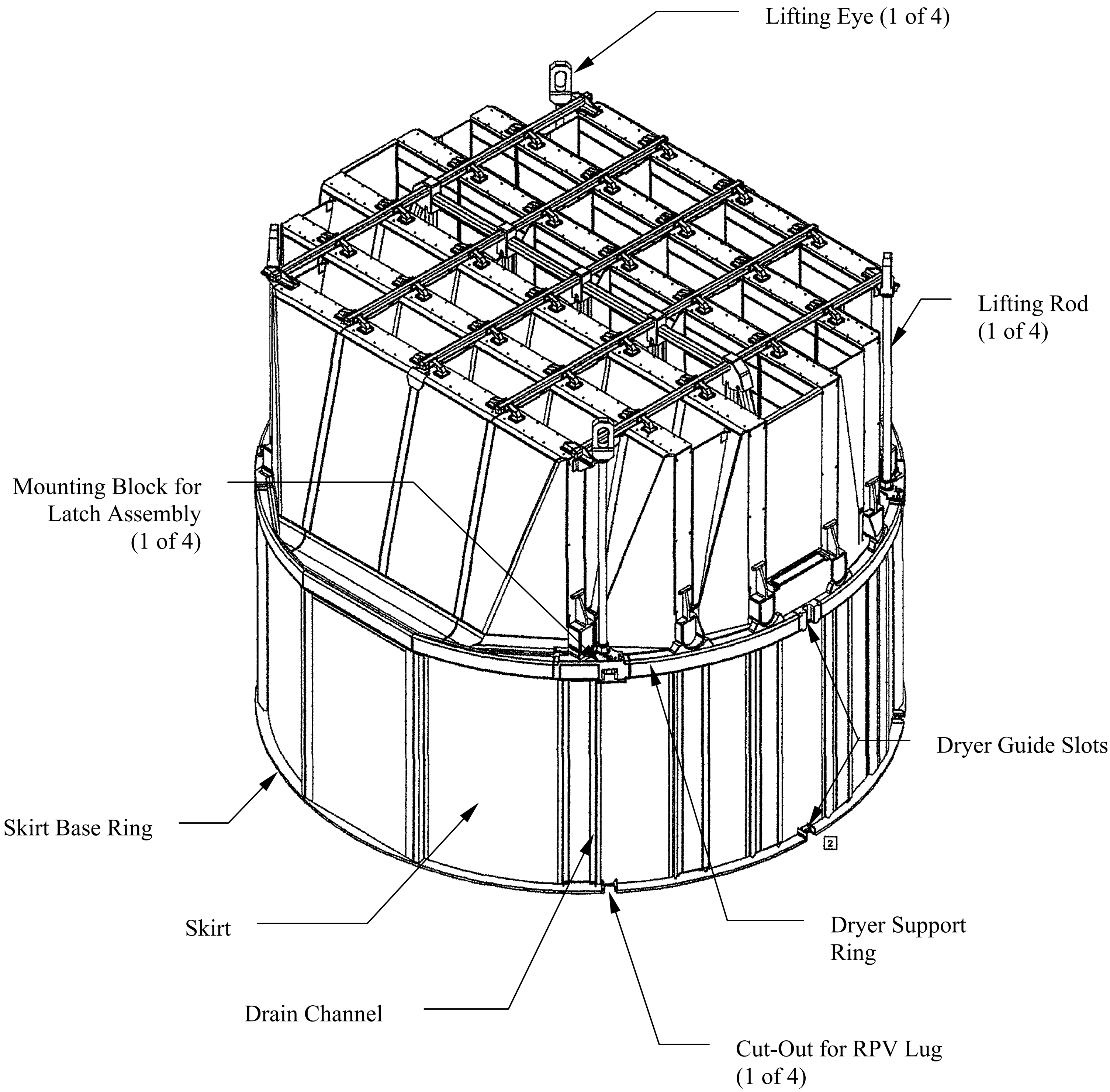


Figure 1: Steam Dryer

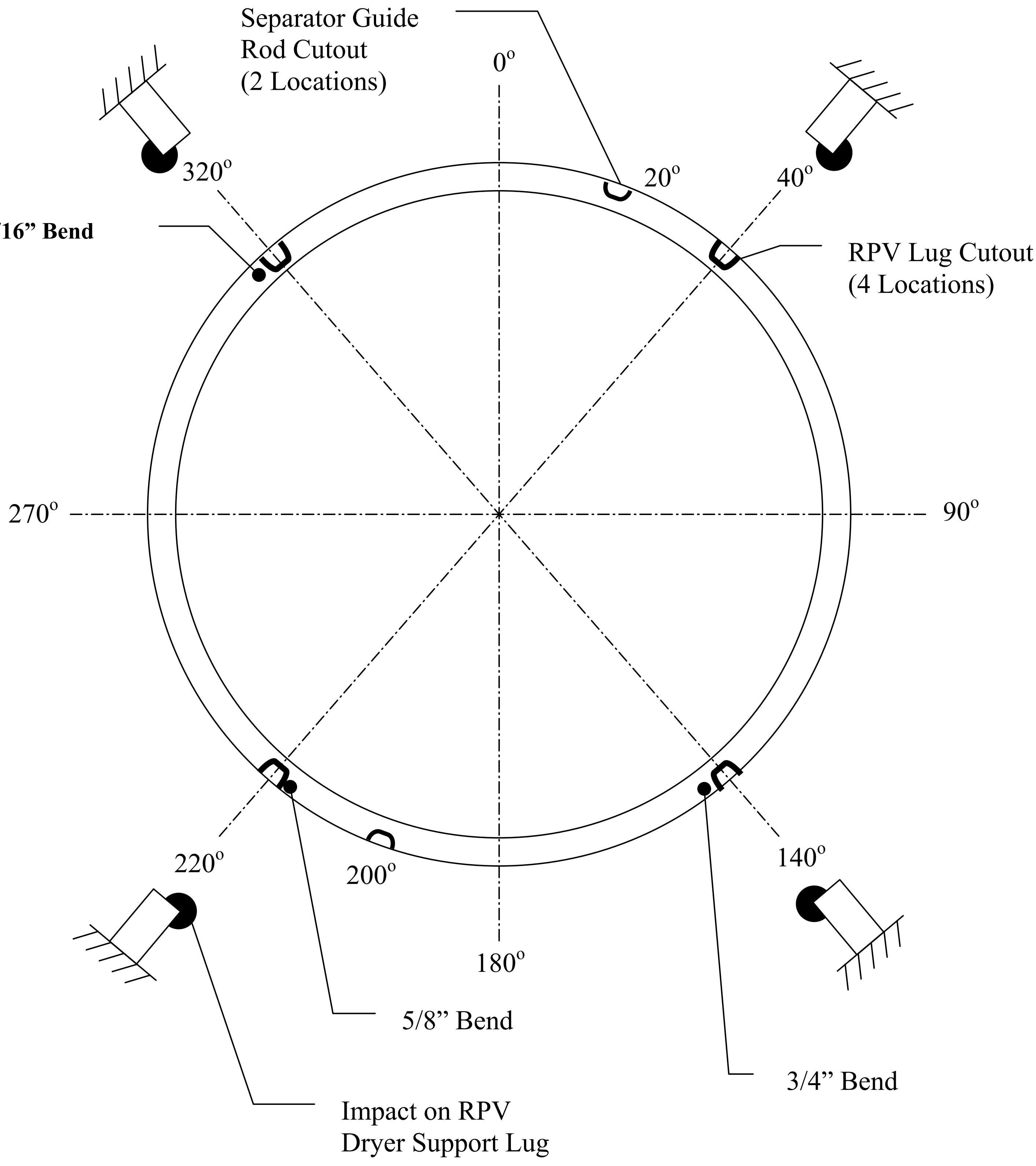
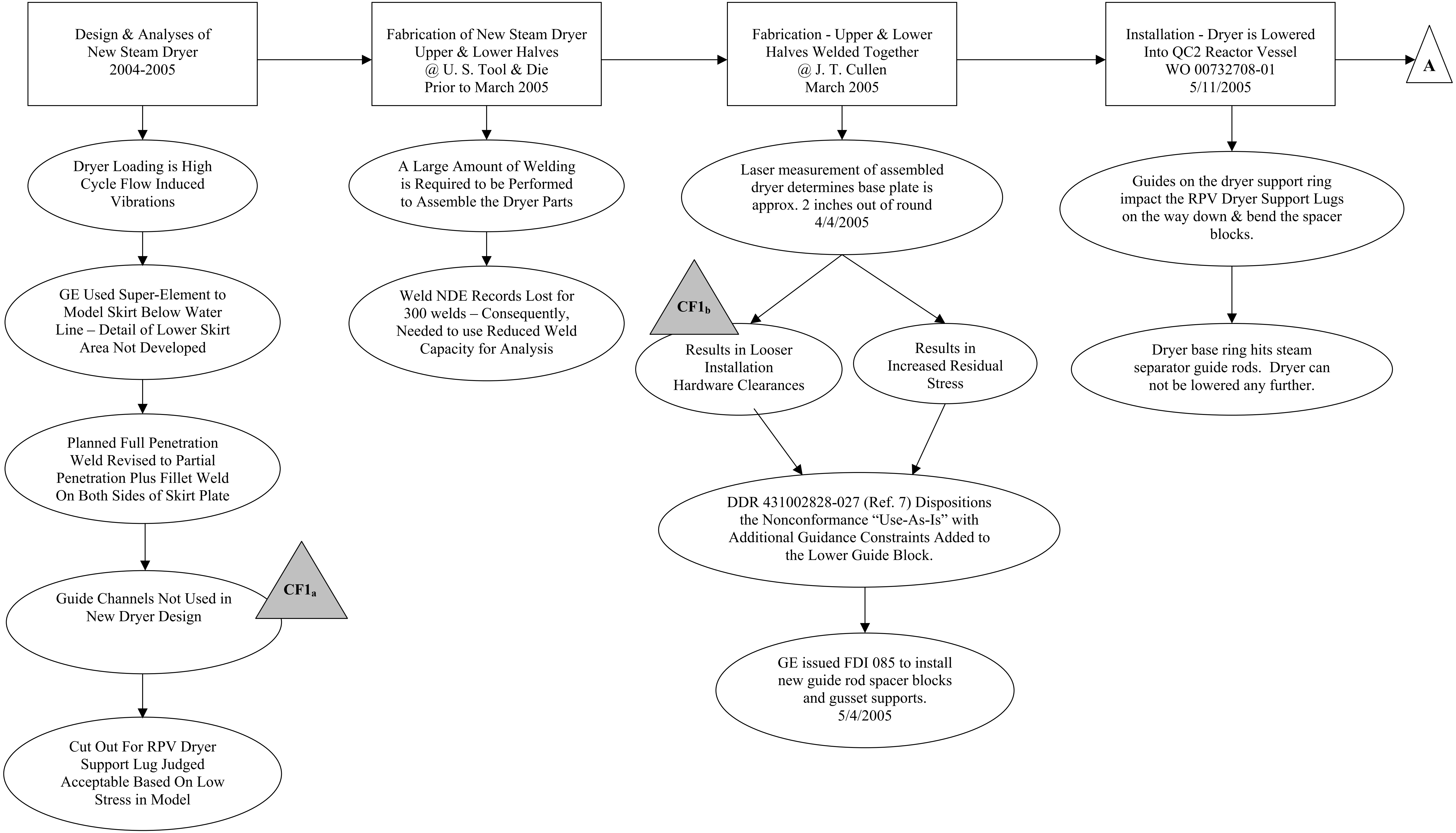
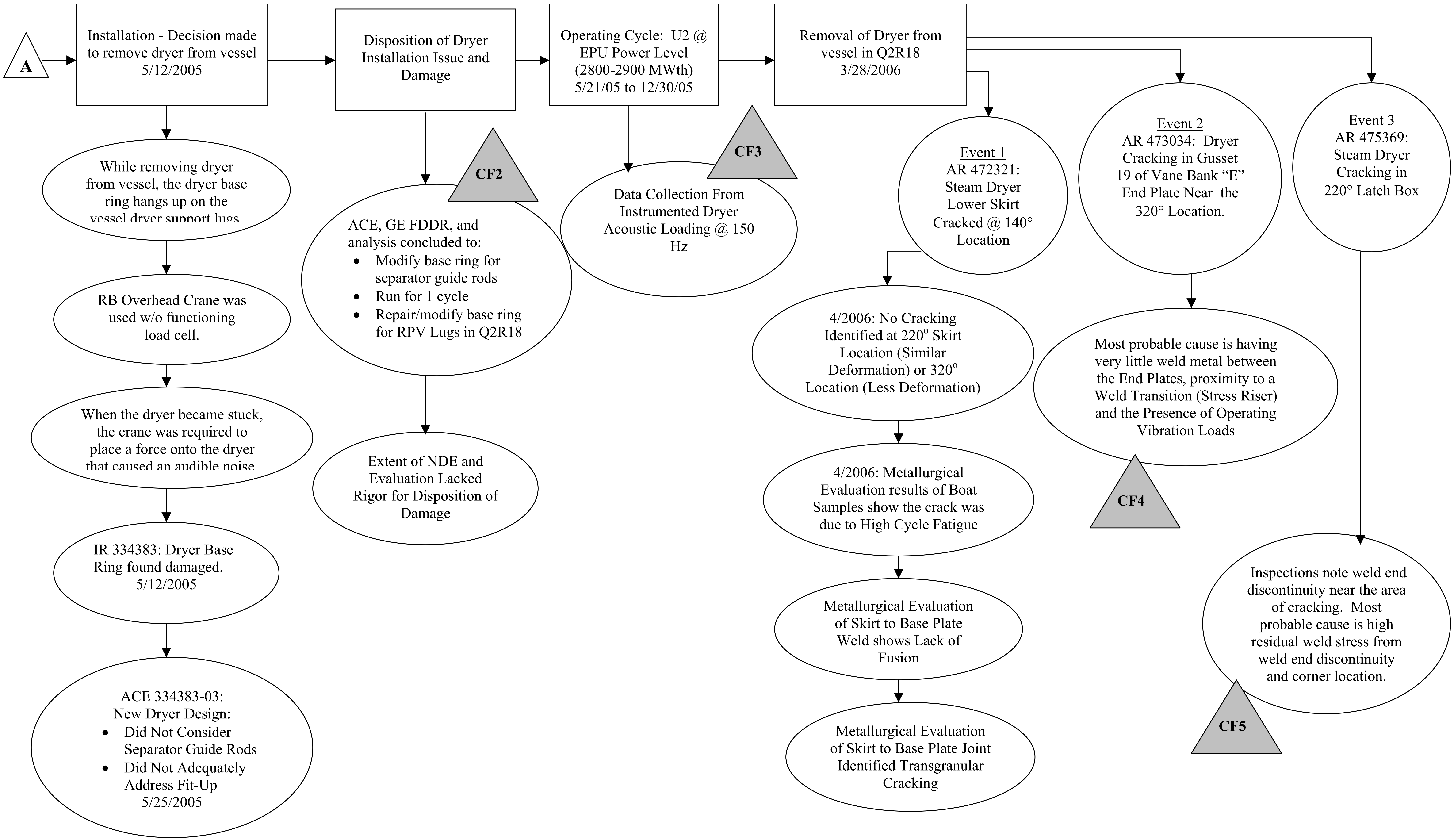


Figure 2 Steam Dryer Plan – Impact Locations



Design & Analyses of New Steam Dryer 2004-2005
Fabrication of New Steam Dryer Upper & Lower Halves @ U. S. Tool & Die Prior to March 2005
Fabrication - Upper & Lower Halves Welded Together @ J. T. Cullen March 2005
Installation - Dryer is Lowered Into QC2 Reactor Vessel WO 00732708-01 5/11/2005
A
Dryer Loading is High Cycle Flow Induced Vibrations
A Large Amount of Welding is Required to be Performed to Assemble the Dryer Parts
Laser measurement of assembled dryer determines base plate is approx. 2 inches out of round 4/4/2005
Guides on the dryer support ring impact the RPV Dryer Support Lugs on the way down & bend the spacer blocks.
GE Used Super-Element to Model Skirt Below Water Line – Detail of Lower Skirt Area Not Developed
Weld NDE Records Lost for 300 welds – Consequently, Needed to use Reduced Weld Capacity for Analysis
CF1b
Results in Looser Installation Hardware Clearances
Results in Increased Residual Stress
Dryer base ring hits steam separator guide rods. Dryer can not be lowered any further.
Planned Full Penetration Weld Revised to Partial Penetration Plus Fillet Weld On Both Sides of Skirt Plate
DDR 431002828-027 (Ref. 7) Dispositions the Nonconformance "Use-As-Is" with Additional Guidance Constraints Added to the Lower Guide Block.
Guide Channels Not Used in New Dryer Design
CF1a
GE issued FDI 085 to install new guide rod spacer blocks and gusset supports. 5/4/2005
Cut Out For RPV Dryer Support Lug Judged Acceptable Based On Low Stress in Model


A
Installation - Decision made to remove dryer from vessel 5/12/2005
While removing dryer from vessel, the dryer base ring hangs up on the vessel dryer support lugs.
RB Overhead Crane was used w/o functioning load cell.
When the dryer became stuck, the crane was required to place a force onto the dryer that caused an audible noise.
IR 334383: Dryer Base Ring found damaged. 5/12/2005
ACE 334383-03: New Dryer Design: • Did Not Consider Separator Guide Rods • Did Not Adequately Address Fit-Up 5/25/2005
Disposition of Dryer Installation Issue and Damage
CF2
ACE, GE FDDR, and analysis concluded to: • Modify base ring for separator guide rods • Run for 1 cycle • Repair/modify base ring for RPV Lugs in Q2R18
Extent of NDE and Evaluation Lacked Rigor for Disposition of Damage
Operating Cycle: U2 @ EPU Power Level (2800-2900 MWth) 5/21/05 to 12/30/05
CF3
Data Collection From Instrumented Dryer Acoustic Loading @ 150 Hz
Removal of Dryer from vessel in Q2R18 3/28/2006
Event 1 AR 472321: Steam Dryer Lower Skirt Cracked @ 140° Location
4/2006: No Cracking Identified at 220° Skirt Location (Similar Deformation) or 320° Location (Less Deformation)
4/2006: Metallurgical Evaluation results of Boat Samples show the crack was due to High Cycle Fatigue
Metallurgical Evaluation of Skirt to Base Plate Weld shows Lack of Fusion
Metallurgical Evaluation of Skirt to Base Plate Joint Identified Transgranular Cracking
Event 2 AR 473034: Dryer Cracking in Gusset 19 of Vane Bank "E" End Plate Near the 320° Location.
Most probable cause is having very little weld metal between the End Plates, proximity to a Weld Transition (Stress Riser) and the Presence of Operating Vibration Loads
CF4
Event 3 AR 475369: Steam Dryer Cracking in 220° Latch Box
Inspections note weld end discontinuity near the area of cracking. Most probable cause is high residual weld stress from weld end discontinuity and corner location.
CF5

Attachment 2 – Event Timeline:

DATE	EVENT/ ACTION	SOURCE DOCUMENT(S)	COMMENTS
Prior to 3/2005	Upper and lower halves of dryer are fabricated at U.S. Tool and Die in Pittsburgh, PA	• NR – common information.	None
3/2005	Upper and lower halves of dryer are welded together at J. T. Cullen, Fulton, IL	• NR – common information	None
4/4/2005	Washington Group begins laser measurements of Assembled Dryer at J. T. Cullen	• Integrated Steam Dryer Project J.T. Cullen Fabrication Facility Daily Activity Sheet	None
4/14/2005	QC2 Dryer Base plate is approximately 2 inches out of round.	• DDR 431002828-027 • EC 351168	Disposition provided 4/25/2005, states, "Clearances normally available have been compromised, so additional guidance constraints will be placed on the lower guide block to limit misalignment and assist in installation."
5/4/2005	GE issues FDI to install new guide rod spacer blocks and gusset supports.	• FDI 0085	Modification of replacement steam dryer to install "additional guidance constraints"
5/11/2005	Lower Dryer into Vessel	• WO 00732708-01	
5/11/2005	Guides on the dryer support ring impacted the RPV Dryer Support Lugs on the way down & bent the spacer blocks	• WO 00732708-01 • AR 334383 • FDDR RMCN 06252	
5/11/2005	Hit Steam Separator Guide Rod with Dryer Base Ring – Dryer could not be lowered any further	• WO 00732708-01 • AR 334348 • FDDR RMCN 06243 • Separator Guide Rod Interference Root Cause Summary (Report Number AI10139) • Apparent Cause Evaluation (ACE) 334348	**Apparent Cause** per ACE: 1. Lack of clearance between dryer base ring and separator guide rods due to wider skirt base ring plate (same OD, smaller ID). 2. Excessive clearance between dryer guide rods and the dryer. • Root Cause Investigation (AR 00330331-03) was supposed to address Steam Dryer design (but did not). • Poor Design was only cause **Corrective Action** per ACE: • Modify dryer per EC 348286 (see 26A6787 Rev. 2 3/7/06)
5/12/2005	Decision made to remove dryer from vessel	• WO 00732708-01	

DATE	EVENT/ ACTION	SOURCE DOCUMENT(S)	COMMENTS
5/12/2005	While removing dryer from vessel the dryer base ring hung up on the vessel dryer support lugs – "Lift Event"	• WO 00732708-01 • AR 334383 • FDDR RMCN 06245 • Prompt Inv. Report	Apparent Cause Evaluation (ACE) Performed under AR 334348
5/13/2005	Reinstallation of dryer into vessel.	• WO 00732708-01	
5/16/2005	Repair of the Reactor Building Overhead Crane Load Cell	• WO 00805641-02	
5/16/2005 Q2C18	Operated at EPU and Pre-EPU power levels	NR – common information	
3/28/2006	U-2 Steam Dryer Lifting Lugs Rotated	• WO 00794824-01 • AR 471848 • INR Q2R18-IVVI-06-01 • Operability Eval. # EC 360272	Op. Eval. scope included IR's: 471848 / 472321 / 473034 / 473344
3/28/2006	Removal of dryer from vessel.	• WO 00794824-01	
3/29/2006	U-2 Steam Dryer Lower Skirt Cracked @ 140°	• WO 00794824-01 • AR 472321 • INR Q2R18-IVVI-06-02	Root Cause Investigation Requested "Event 1"
3/30/2006	U-2 Indications Identified on Steam Dryer Gusset	• WO 00794824-01 • AR 473034 • INR Q2R18-IVVI-06-04	"Event 2"
4/05/2006	U-2 Steam Crack at 220° Latch Box	• WO 00794824-01 • AR 475369 • INR Q2R18-IVVI-06-29	"Event 3"

Attachment 3 – References

Ref. #	Document Reference Number	Title / Description
1	WO 00732708-01 EC 351168	Replace Unit-2 Steam Dryer Per EC 351168
2	AR 334383	May 2005, ACE on Q2P03 Dryer Lifting Event
3	FDDR RMCN 06252	GE disposition of steam dryer interferences between the vessel steam dryer support lug and the lug spacer block.
4	AR 334348	May 2005 Prompt Investigation of Q2P03 Dryer Lifting Event
5	FDDR RMCN 06243	GE disposition of Steam Separator Guide Rod Interference with the Base Ring of the Steam Dryer Skirt.
6	GE Report Number AI10139	GE Root Cause Summary: Separator Guide Rod Interference
7	DDR 431002828-027	GE Disposition of "Ovality" Issue: Steam Dryer Final Dimension Approximately 2 Inches Out of Round.
8	FDDR RMCN 06245	GE disposition of May 2205, Q2P03 Lift Event
9	FDI 0085, Rev. 0 and Rev. 1	Engineering requirements and instructions for the modifications of the replacement steam dryer to be installed at QC Unit 2 prior to the Q2P03 dryer replacement outage. (Modified Jack Bolts, Installed Guide Rod Spacer Blocks, and Gusset Supports.)
10	AR 472321	Q2R18 Identified Crack In The U2 Steam Dryer Skirt. ("Event 1" of this RCA.)
11	INR Q2R18-IVVI-06-02	Steam Dryer Skirt @135 Degrees (Note: Most Later References Specify 140°)
12	AR 473034	Q2R18 IVVI – Indications on Steam Dryer Gusset (E-Bank End Plate Crack). ("Event 2" of this RCA.)
13	INR Q2R18-IVVI-06-04	Steam Dryer Bank E ID
14	AR 475369	Q2R18 Identified 220 Degree Latch Box Crack ("Event 3" of this RCA)
15	INR Q2R18-IVVI-06-29	220 Degree Latch Box Crack
16	GENE 0000-0053-1962	GE Review of Transgranular Stress Corrosion Cracking in Skirt to Base Weld Root Area
17	GE-NE-0000-0052-9728	GE Evaluation of the Bank E Drying Vane End Plate Crack ("Event 2" of this RCA.)
18	GE-NE-0000-0053-0232	QC U-2 Replacement Steam Dryer Analysis Evaluation of Latch Box Cracking and Fatigue Impact of Swing Arm & Latch Protector Welds ("Event 3" of this RCA)
19	GE-NE-0000-0052-9666	QC U-2 Replacement Steam Dryer Metallurgical Evaluation

Ref. #	Document Reference Number	Title / Description
20	GE-NE-0000-0052-6385-RO	Lost Parts Analysis for Potential Lost Dryer Lifting Eye and Dryer Skirt Panel Quad Cities U-1
21	GE-NE-0000-0053-2926	Root Cause Analysis for QC2 Steam Dryer 140° Skirt Cracking (“Event 1” of this RCA)
22	DDR dated 02/20/2005	Dryer Support Ring 3/8” Out of Flat due to Welding Distortion.
23	GE LFW0505-2, May 20, 2005, DRF 0000-0034-3781	Quad Cities U-1&2 Replacement Dryer Skirt Cutouts: (Discusses modifications needed to both U-1 and U-2 replacement dryers as a result of Q2P03 Issues.)
24	GE Transmittal No. JXD4E-023 dated 4/28/2005	As-Built Dimensional Analysis, QC-2 Steam Dryer (Report describing why the U-2 Replacement Dryer will fit in the vessel despite the ovality issue)
25	GE-NE-0000-0034-4803-02	Replacement Steam Dryer Reactor Vessel Bracket Stress Report for Quad Cities 1,2 and Dresden 2,3”, April 2005.
26	RM Documentation No. SA-1477	Risk Assessment for IR 473034 and IR 472321, Steam Dryer Gusset Cracking and Steam Dryer Skirt Cracking, Assignment 03 Root Cause Report.
27	GENE 0000-0052-8407 & 8408	GE Steam Dryer – Recommendation for Repairs at 220 ° & 320° Locations (2 documents – same topic)
28	FDDR RMCN08436	Q2R18 Addition of Dryer Guide Rod Block Extensions
29	GE-NE-0000-0053-2910	QC U-2 Replacement Steam Dryer Analysis Detailed Stress Analysis of Skirt Base Plate Cutout and Gussets, April 2006
30	Exelon-ENG-DRY-099CR	Exelon Concurrence with GE Resolution of U-2 Steam Dryer Collision Damage. Dated May 24, 2005.
31	GENE-0000-0052-7988 Rev. 2	Q2R18 Steam Dryer ID Welds Flaw Evaluation, April 2006.
32	FDDR RMCN08404	“Ring and Skirt Assembly”, dated 04/05/06. (Specifications and drawings for repair to 220° area.)
33	GENE 0000-0053-0605-1	QC2 Steam Dryer – Base Ring Diametral Distortion (April 2006 re-assessment of ovality issue)
34	GENE 0000-0053-0606	QC2 Steam Dryer Repair Crevice Assessment (Discussion of acceptability of skirt plate repairs using backing rings).
35	GENE 0000-0043-3105-01-P	QC U-2 Replacement Steam Dryer Stress and Fatigue Analysis Based on Measured EPU Conditions (July 2005)
36	GE-NE-0000-0053-2456-P	QC U-2 Replacement Steam Dryer Analysis Detailed Stress Analysis of Dryer Lifting (April 2006)
37	AR 330331	RCA: “QC2 Replacement Steam Dryer Impact on Fuel Analysis Results”
38	AR 435858	RCA: “Electromatic Relief Valve Solenoid Actuator Failures due to failure to correct the source of the MSL vibrations …”
39	EC 360876	Review of Q1M19 Critical Steam Dryer Inspection Findings

Ref. #	Document Reference Number	Title / Description
40	GENE 0000-0053-2954, Revision 1	Request for Additional Information: QC U-2 Dryer Inspection, Start-up & Power Ascension Plan – RAI 9 (b): Discussion of the corresponding reduction in the fatigue stress limits in the Dryer Skirt Crack.
41	Ref. 3 used in GENE 0000-0053-2954, Rev. 1 – RCA Ref. 40 (above)	Manjoine, M.J. and Tome, R.E., "Proposed Design Criteria for High Cycle Fatigue of Austenitic Stainless Steels," International Conference on Advances in Life Prediction Methods, ASME, 1983, pp. 51-57.

Attachment 4: Comparison of QC 2 Replacement Steam Dryer Pressure Sensor Data with Q2R18 Dryer Damage.

Reason For Evaluation / Scope:

Note: The references in this attachment refer to the items listed on the final page of this attachment, not the RCA Report references listed in Att. 3

Quad Cities Unit 2 (Q2) new steam dryer was installed in May 2005 under EC 351168 (Ref. 1). During installation of the new steam dryer, AR 334348 (Ref. 2) identified that the new steam dryer would not sit in the dryer guides properly. The dryer was repaired and the skirt base plate deflection was documented in GE Traveler (Ref. 3). The skirt base plate deflection at the 140^0 AZ location is ¾", at 220^0 AZ location: 5/8", and at 320^0 location: 5/16". At the 40^0 AZ location, no plastic deformation of the skirt base plate was noted. At 140^0 AZ, the skirt base plate cutout plastically deformed ¾" downward with visible inside diameter (ID) deformation and skirt panel with dimple at top of gusset. At 220^0 AZ, the skirt base plate was deformed 5/8" downward with visible ID deformation and no evidence of dimpling. At 320^0 AZ, the skirt base plate was deformed 5/16" downward with imperceptible plastic ID deformation

Q2 steam dryer is instrumented with strain gages, pressure sensors, and accelerometers. GE Specification 26A6395 (Ref. 4), sheets 15, 16, 17, and 18 provides the sensor locations with respect to the Dryer orientation in the reactor vessel and its relative elevations. During unit start up testing to full power, AR 347867 (Ref. 5) identified that various strain gages and accelerometers were failing. After completion of the testing, Q2 ran at full power for > 200 days before coming down for a planned refueling outage (Q2R18).

Further, inspection of the steam dryer in Q2R18 indicated damage to the dryer skirt (AR 472321) (Ref. 6) and dryer lifting lugs rotated (AR 471848) (Ref. 7). The #7 skirt panel and base plate at cutout cracked after ~200 days of EPU operation. At 25 Hz, the skirt base plate and the skirt panel #7 have undergone 4.3e08 cycles

Purpose of this evaluation is to a) review Q2 start up test data and compare it with the damage seen on the steam dryer skirt at locations close to the main steam lines (MSL) and b) to see whether the as-built/as-installed dryer with known damage to the skirt base plate could affect the pressure distribution in the steam space external to the dryer and affect the main steam line frequency patterns at the full load operation of the unit.

Detailed Evaluation:

The new steam dryer orientation was taken from reference 4, sheet 17. Drawing M-3121 (Ref. 8) identifies main steam line nozzle orientation. It should be noted that "A" MS nozzle at 70^0 is closest to 40^0 dryer skirt base plate cutout. Similarly, "B" MS nozzle at 110^0 is closest to 140^0 dryer skirt base plate cutout; "C" MS nozzle at 250^0 is closest to 220^0 dryer skirt base plate cutout; and "D" MS nozzle at 290^0 is closest to 320^0 dryer skirt base plate cutout.

Following Table shows the pressure sensors located external to the steam dryer, MSL locations, and other pertinent data. Also, Document Number AM-2005-012 (Ref. 9) shows actual pressure data taken from Quad Cities Unit 2 start up testing. This pressure data is used in developing the overall evaluation.

•Q2 dryer pressure sensor locations:

- P3 A hood, opposite "B" MS nozzle.
- P22, P24, & P25 skirt below "B" MS nozzle.
- P12 A hood, opposite A MS nozzle.
- P20 F hood, opposite 'C" MS nozzle.
- P21 F hood, opposite D MS nozzle.
- P15 & P17, hood Closure Plate- B & C hoods.

TABLE

No.							
1	Main Steam Line (Ref. 8)	**A**	**A**	**B**	**B**	**C**	**D**
2	MSL Azimuth	70^0	70^0	110^0	110^0	220^0	290^0
3	Dryer Skirt Base Plate Cutout Location	40^0	40^0	140^0	140^0	220^0	320^0
4	Initial Skirt Base Plate Damage	None	None	¾ Inch	¾ Inch	5/8 Inch	5/16 Inch
5	External Pressure Sensors on Dryer	P12	N/A	P3	N/A	P20	P21
6	External Pressure Sensors on Dryer Skirt above Water Line	N/A	P25	N/A	P22	N/A	N/A
7	Min. Pressure, psi (Ref. 9)	-2.069	-1.270	-1.887	-1.379	-1.613	-2.261
8	Max. Pressure, psi (Ref. 9)	1.907	1.166	1.817	1.243	1.588	2.099
9	Δ Pressure, psi	3.976	2.436	3.704	2.622	3.201	4.360
10	RMS Pressure Measured, psi (Ref. 9)	0.69	0.344	0.631	0.422	0.499	0.883
11	ERV(s) on MSL			2-0203-3B & 2-0203-3E		2-0203-3C	2-0203-3D
12	ARs on ERV	None		435838		435838	430555 and 435838

Conclusions/Recommendations:

a) Review of reference 4 shows pressure sensor locations on the dryer from higher to lower elevation in the following order: P1, P2, P3, P22, and P24. Further review of this reference shows that the pressure sensors P3, P6, P9, P12, P15, and P17 are located 65" below the top of Bank "A". Review of the pressure data from reference 9 for these sensors indicate that pressure reduces when moving downward and when moving away from steam nozzles. Pressure at 140^0 location (P3) is lower than pressure at 70^0 or 290^0

locations (P12 and PP21). Skirt pressures are lower than hood pressures as seen from pressure sensor data of P22, P25, P3, and P12. Steam pressure measured at the skirt (P25 and P22) is lower by order of two when compared with the pressures measured at the hood (P12 and P3). Further, the Table shows that steam pressure will be highest for the "D" MSL nozzle, then "A", "B" and the lowest steam pressure will be at "C" MSL nozzle. (i.e., Pressure loads closer to "D" & "A" steam nozzles are greater than the "B" & "C" steam nozzles).

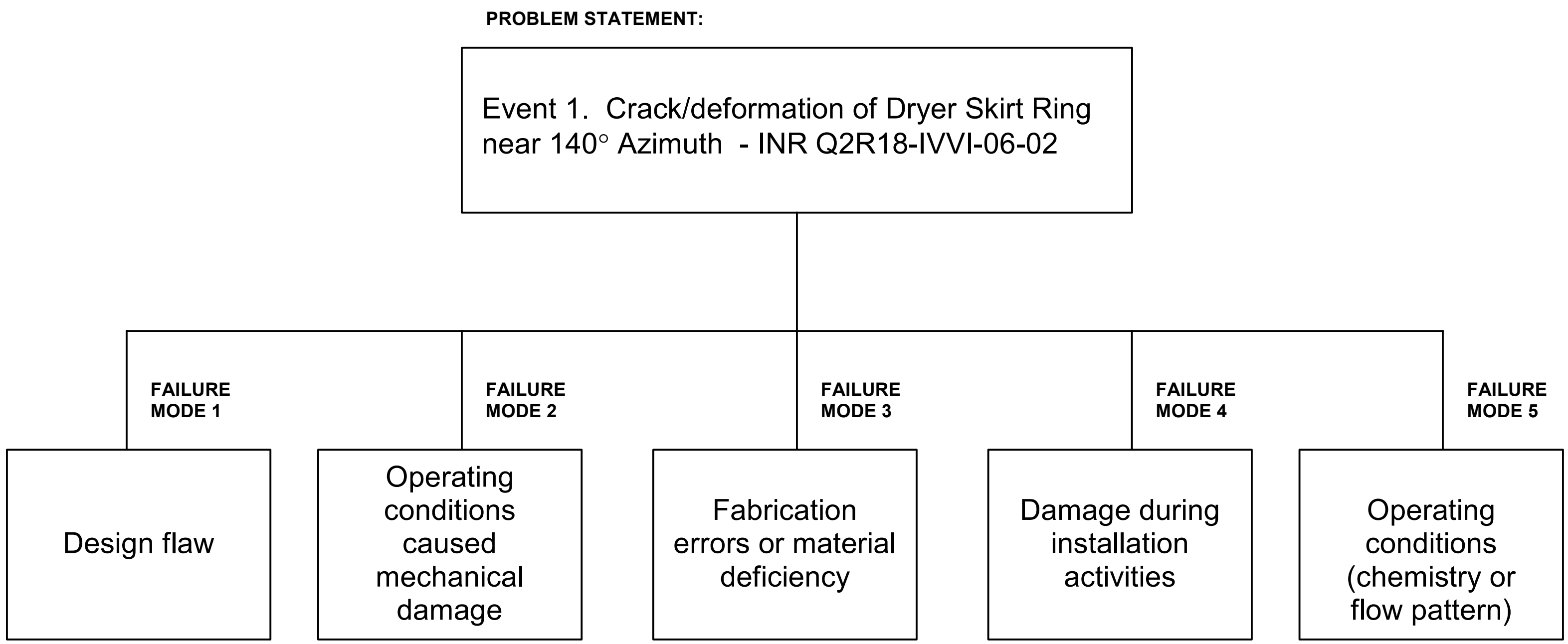
b) Based on the pressure data, it can be concluded that although the dryer skirt base plate at 320^0 AZ has a 5/16" bend and the highest measured pressure (P21 = 4.63 psi), no crack was found. However, at 140^0 AZ, the dryer skirt base plate has highest bend (¾") and lower measured pressure (P3 = 3.704 psi), yet a large crack in the skirt plate # 7 was noted. Therefore, it can be concluded that pressure oscillations alone could not be the primary cause of the crack initiation and/or propagation.

Further, review of Quad Cities Unit 2 Electromatic Relief Valve (ERV) ARs indicate that ERV 2-0203-3D on "D" MSL has seen more damage than 2-0203-3B and 2-0203-3E on "B" MSL and 2-0203-3C on "C" MSL. However, ERVs on "B" and "C" MSLs also have seen some failures. This evaluation confirms the conclusion reached in Report AM-2005-014 (Ref. 10) which states that "Tables 1 and 2 seem to provide reasonable results in that the normalized flow through Main Steam Lines "A" and "D" are higher than "B" and "C" for both units. This is expected since the "A" and "D" Lines are the shorter Main Steam Lines."

References:

1) EC 351168, Rev. 2: Unit 2 Steam Dryer Replacement.
2) AR 334348: PSU – Steam Dryer would not set all the way down.
3) GE Traveler, Project KCZKU, Traveler No. KCZKU-Base Ring Deflection.
4) GENE Design Specification 26A6395, Rev. 2: Dryer Vibration Instrumentation
5) AR 347867: New steam Dryer Strain Gages/Accelerometers are failing.
6) AR 472321: PSU Q2R18 Crack in the U2 Steam Dryer Skirt.
7) AR 471848: PSU Q2R18 U-2 Steam Dryer Lifting Lugs Rotated.
8) QC Drawing M-3121, Rev F: In-service Inspection Isometric Reactor Vessel
9) Document Number: AM-2005-012, Rev 0 An Assessment of the Uncertainty in the Application of the Modified 930 MWe Acoustic Circuit Model Predictions For the Replacement Quad Cities Units 1 and 2 Steam Dryers.
10) Report AM-2005-014, Rev. 0, dated July 20, 2005: Quad Cities Unit 2 New Steam Dryer Outage Startup Test Report.

Att. 5 – Event 1: Failure Mode Tree Ref: MA-AA-716-004 Att.2



Att. 5 – Event 1: Failure Mode Tree   Ref: MA-AA-716-004 Att.2

Failure Mode No. 1   **Description Design Flaw**

	Cause(s)	Validation/Action Steps	Results *Expected results are based on system operation as designed, not as failed Expected	 Actual	Owner Status
A	Finite element model error allowed unacceptable stress level to be accepted	RIGOR (A, B, C, D, N/A) D Validate model IAW GE method requirements Independent review or model output	Model valid Review confirms	1) Validated 2) Validated	GE RCA - complete Rich Hall – complete
B	Incorrect tolerances to allow for: 1) fit-up 2) heat-up/operational movement	RIGOR (A, B, C, D, N/A) D 1) Determine the role of Design in the known impact of new dryer with RPV lugs, and separator guide pins. Structural analysis and metallurgical testing to determine if this initiated crack. 2) Review for evidence of rubbing of components due to expansion or operational forces.	1) Impact had role in crack initiation. 2) No evidence.	1) Confirmed as a CF. 2) No evidence.	RCA - complete RCA - complete

Att. 5 – Event 1: Failure Mode Tree Ref: MA-AA-716-004 Att.2

Failure Mode No. 1 **Description Design Flaw**

	Cause(s)	Validation/Action Steps	Results *Expected results are based on system operation as designed, not as failed — Expected	Actual	Owner Status
C	Inadequate load definition caused localized high stress during design operating conditions	RIGOR (A, B, C, D, N/A) D Review of model for design margin preventing plastic deformation	No plastic deformation predicted	Confirmed	GE RCA - complete
D	FDDR RMCN 06243 incorrectly allowed use of the machined ring slot with strength reduced more than assumed	RIGOR (A, B, C, D, N/A) D Confirm conclusions of FDDR RMCN 06243 that amount of metal removed still leaves adequate strength per design requirements including dynamic loads a) How did the load redistribute b) What material impacts when grinding (GE materials, what impact fatigue life for comp that exceeded 0.2% plastic strain) Note: Unless metallurgical analysis specifies the presence of IGSSC, grinding and machining are not a CF.	Material strength adequate	Confirmed as not an initiating event.	GE RCA - complete

Att. 5 – Event 1: Failure Mode Tree   Ref: MA-AA-716-004 Att.2

Failure Mode No. 2	Description: Operating conditions (mechanical)				
			Results *Expected results are based on system operation as designed, not as failed		Owner Status
	Cause(s)	Validation/Action Steps	Expected	Actual	
A	Low quality steam output at the steam separator causes high moisture momentum load to dryer	RIGOR (A, B, C, D, N/A) D Confirm mechanical load from moisture carry-over is less than the design limit for dryer components including the cyclic effect of 0.3 Hz core power cycles.	Adequate margin exists	No moisture carryover concerns identified.	RCA screened as low probability. Closed
B	Transient event ADS/TG blowdown and rapid pressure change or dryer overload Single MSIV closure at power causing an asymmetric load	RIGOR (A, B, C, D, N/A) D Review cycle history curve for SRV or BPV transients and confirm that transient loads do not exceed internal load limit and dryer lift limit Review cycle history curve for asymmetric MSL flows or higher single MSL flow noise	No blowdown or transient loads in excess of limits Steady-state or transient asymmetrics insignificant	Review of power history did not identify any transients of concern.	RCA screened as low probability. Closed

Att. 5 – Event 1: Failure Mode Tree   Ref: MA-AA-716-004 Att.2

Failure Mode No. 2 Description Operating conditions (mechanical)					
	Cause(s)	Refer to Attachment 4 for examples of risk and rigor determination for steps below Validation/Action Steps	Results *Expected results are based on system operation as designed, not as failed Expected	Actual	Owner Status
C	Cyclic power loads induce high cycle fatigue MSL resonance RR bistable flow power swings cause cycle dryer load	RIGOR (A, B, C, D, N/A) D Evaluate MSL flow swings causing cyclic loading of total dryer dP to induce fatigue Power changes from sitting with RR bistable flow	Fatigue load has large margin Fatigue load has large margin	Closed	RCA screened as low probability based on factors including evaluation in Att. 8 Closed
D	Power/Flow Anomaly High subcooling causes low core exit quality High Flow Control Line (FCL) causes high core dP	RIGOR (A, B, C, D, N/A) D Compare core average exit quality (CAEQ) to previous cycles (moisture carryover) Compare FCL for cycle to previous cycles	CAEQ change from previous cycles minimal	Closed	RCA screened as low probability. Closed

Failure Mode No. 3 Description Fabrication error or material deficiencies					
	Cause(s)	Validation/Action Steps	Results *Expected results are based on system operation as designed, not as failed Expected	Actual	Owner Status
A	Distortion/ovality of Cullen fit-up and weld of base to skirt	RIGOR (A, B, C, D, N/A) D 1. Calculate the loads imposed by fit-up with as-built ovality. (GE to address this in analysis) 2. Determine impact of ovality in reducing clearances and influencing lift event.	1. No loads exceed design limits. 2. Ovality impact of reduced clearance is a CF.	Confirmed as not a CF Confirmed as a CF	1. GE RCA - complete 2. RCA team - complete
B	Incorrect or substandard materials were used or supplier errors or process control failures	RIGOR (A, B, C, D, N/A) D Confirm that materials match the design requests and that sub component supplier certifications/procurement records	1. Records confirm proper materials and controls 2. Metallurgical analysis confirms no material deficiency.	1. Confirmed 2. GE testing indicates that the materials are consistent with drawings and CMTRs.	GE analysis - complete

Att. 5 – Event 1: Failure Mode Tree Ref: MA-AA-716-004 Att.2

Failure Mode No. 3 **Description Fabrication error or material deficiencies**

	Cause(s)	Validation/Action Steps	Results *Expected results are based on system operation as designed, not as failed — Expected	Actual	Owner Status
C	Incorrect component fabrication or techniques	RIGOR (A, B, C, D, N/A) D Confirm dryer fabrication records match approved processes	No discrepancies identified as CFs.	DDR reviews no issues as CFs problems.	Summary review completed. RCA screened as low probability. Closed
D	Incorrect fabrication sequence	RIGOR (A, B, C, D, N/A) D Confirm fabrication sequences did not cause interim overstresses such as unsupported spans, temporary jacking etc.	No discrepancies identified as CFs.	DDR reviews no issues as CFs problems.	RCA screened as low probability. Closed

Failure Mode No. 4 **Description Damage during installation**

	Cause(s)	Validation/Action Steps	Results *Expected results are based on system operation as designed, not as failed Expected	 Actual	Owner Status
A	Interference/overload stresses cause excess load during lift Uneven lift loads concentrate load localized area at 140° location causes distortion	RIGOR (A, B, C, D, N/A) D 1. Calculate the loads on the skirt ring, gusset, skirt panel 2. Confirm dryer internal loads with single point "hung up" and weight distributed does not overstress skirt ring 3. Metallurgical analysis of dryer materials.	No overstress during lifting incident No overstress during installation activities	No determination of overstress, but lifting event impacts on material is most probable initiating event.	1&2. GE RCA complete 3. Vallecitos complete Rich Hall (ITPR) Complete
B	Rotation/torsion applied during installation caused localized overstress	RIGOR (A, B, C, D, N/A) D Obtain description of "manual rotation" used, calculate possible torsion loads	Torsion induced loads were minimal	Torsion induced loads were minimal	RCA screened as low probability. Closed

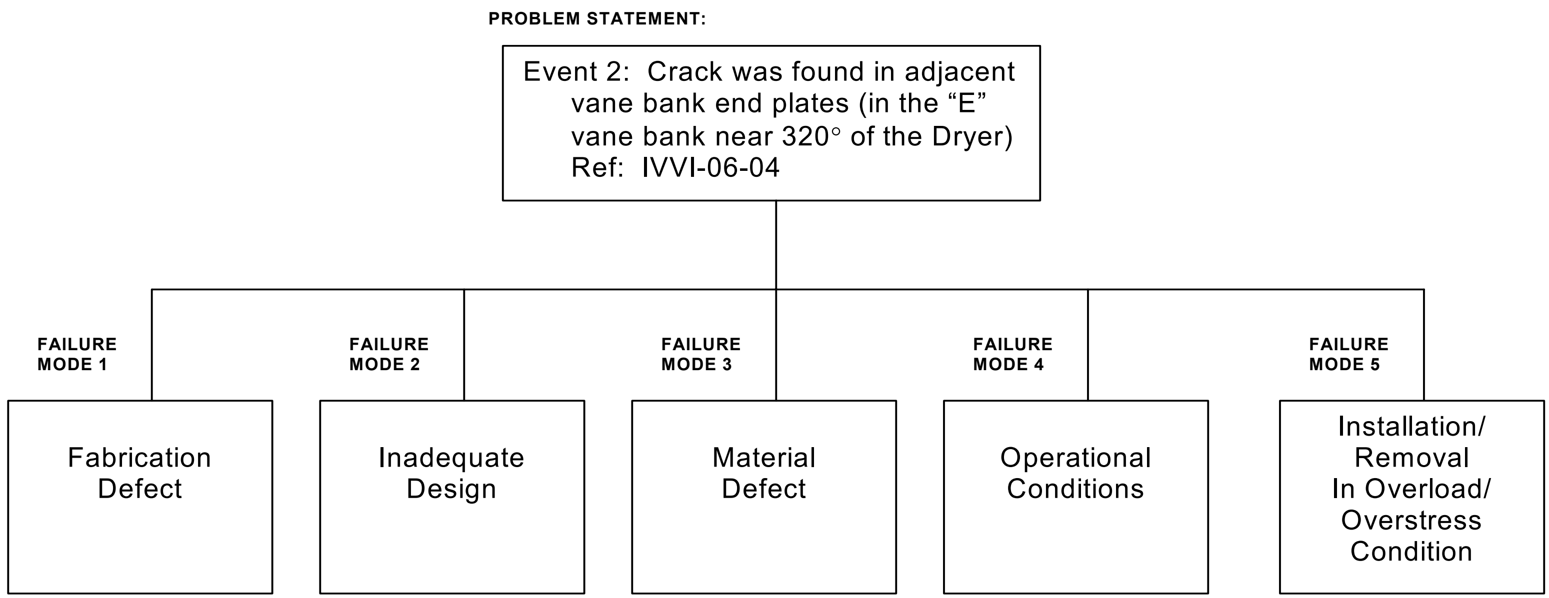
Att. 5 – Event 1: Failure Mode Tree Ref: MA-AA-716-004 Att.2

Failure Mode No. 4	Description Damage during installation				
			Results *Expected results are based on system operation as designed, not as failed		Owner Status
	Cause(s)	Validation/Action Steps	Expected	Actual	
C	Uneven weight distribution while sitting on 2 RPV lugs caused load concentration exceeding limits	RIGOR (A, B, C, D, N/A) D Calculate loads/flex caused by sitting on 2 RPV lugs (Note: Considered a lower priority analysis unless other analysis is inconclusive).	No gusset or skirt ring overstressed	Confirmed	GE RCA complete
D	RB Crane load cell visual display not working during dryer installation.	RIGOR (A, B, C, D, N/A) D Determine impact of inoperable load cell on lift event.	Load cell inoperable is not a CF but included in “Other” section.	Not a CF	Site RCA - complete

Att. 5 – Event 1: Failure Mode Tree Ref: MA-AA-716-004 Att.2

Failure Mode No. 5 Description Operating Conditions (chemistry or flow)					
			Results *Expected results are based on system operation as designed, not as failed		Owner Status
Cause(s)		Validation/Action Steps	Expected	Actual	
A	Core design issues, power distribution increased local moisture but was damaged by moisture momentum	RIGOR (A, B, C, D, N/A) D Compare core operating conditions to as named service conditions	No discrepancy between design and operation	Closed	RCA screened as low probability. Closed
B	Steam separator local blockage caused uneven loading (increased flow in part, decreased other)	RIGOR (A, B, C, D, N/A) D Inspect steam separator for blocked flow path	No blocked separator tubes	Closed	RCA screened as low probability. Closed

Att. 6 – Event 2: Failure Mode Tree Ref: MA-AA-716-004 Att. 2



Att. 6 – Event 2: Failure Mode Tree Ref: MA-AA-716-004 Att. 2

Failure Mode No. 1 Description **Fabrication Defect**					
	Cause(s)	**Validation/Action Steps**	**Results** *Expected results are based on system operation as designed, not as failed **Expected**	 **Actual**	**Owner Status**
A	High stress condition or stress riser created by inappropriate weld or other fabrication error	RIGOR (A, B, C, D, N/A) D Inspect failed area visually for location or indication of any crack initiation or defect	No crack initiation site or defect identified	Potential CF: INR Page 2 last picture shows a location where there is very little weld material and this point appears to be the initiation site for the crack*	GE RCA - Complete

* Based on these inspection results, it can be concluded that having very little weld metal between the end plates at gusset 19 contributed to the initiation and propagation of the crack in this location. This incomplete weld combined with hood assembly fit-up and weld shrinkage stresses, and the deformation and loading associated with the interferences during dryer removal are the most probable cause of the crack initiation that would then have been driven to its current size by operating vibration loads.

Att. 6 – Event 2: Failure Mode Tree Ref: MA-AA-716-004 Att. 2

Failure Mode No. 2	**Description Inadequate Design**				
			Results *Expected results are based on system operation as designed, not as failed		**Owner Status**
Cause(s)		**Validation/Action Steps**	**Expected**	**Actual**	
A	Crack occurred in area subjected to overstress (Finite Element Analysis incorrect)	RIGOR (A, B, C, D, N/A) D Stress analysis to identify loading/stresses in area	Stress is within allowable limits	Confirmed	GE RCA complete.

Failure Mode No. 3	**Description: Material Defect**				
			Results *Expected results are based on system operation as designed, not as failed		**Owner Status**
Cause(s)		**Validation/Action Steps**	**Expected**	**Actual**	
A	Defects in plate material created stress riser or highly localized stress	RIGOR (A, B, C, D, N/A) D Inspect plate for evidence of fracture initiation location, fretting or fatigue	Failure not due to material defect	Closed	RCA screened as low probability. Closed

Failure Mode No. 4 **Description: Operational Conditions**

	Cause(s)	Validation/Action Steps	Results *Expected results are based on system operation as designed, not as failed		Owner Status
			Expected	**Actual**	
A	Operating conditions caused vibrations that exceeded the design capabilities of the vane bank end plate	RIGOR (A, B, C, D, N/A) D Verify appropriate operating conditions were modeled in analysis	Operating conditions were appropriately modeled	Closed	RCA screened as low probability. Closed

Failure Mode No. 5 **Description Installation/Removal in Overload/Overstress Condition**

	Cause(s)	Validation/Action Steps	Results *Expected results are based on system operation as designed, not as failed		Owner Status
			Expected	**Actual**	
A	Excessive loads were placed on the vane bank end plates when the Steam Dryer was resting on the Steam Separator Guide Rods	RIGOR (A, B, C, D, N/A) D Determine the load that was applied to the vane bank end plate during the incident.	The load was within the design limits of the vane bank end plate	Analysis concludes this is not a CF.	GE RCA complete
B	Excessive loads were placed on the vane bank end plates when the Steam Dryer was stuck on the RPV lugs	RIGOR (A, B, C, D, N/A) D Determine the load that was applied to the vane bank end plate during the incident.	The load was within the design limits of the vane bank end plate	Analysis concluded this is not a CF	GE RCA complete

Att 7: Dryer to Dryer Lug Impact Analysis (Lifting Event)

Background: During the initial installation of the Quad Cities Unit 2 dryer, the dryer became "hung up" on the dryer lugs. During the initial dryer placement, it was discovered that the dryer base plate interfered with the separator guide rods. As a result, the dryer was removed to allow the base plate to be modified to prevent the interference. During the lift, the dryer base plate became hung up on the dryer lugs. The interference resulted in damage to the dryer lugs and local yielding of the dryer base plate.

Evaluation: There are four dryer support lugs on the ID of the reactor vessel and four guide slots in the dryer base plate. The guide slots are intended to allow the dryer base plate to move by the dryer support lugs during lowering and lifting. The support lugs and guide slots are located at 40°, 140°, 220°, and 320° azimuths around the ID of the reactor vessel and the OD of the dryer base plate, respectively.

The dryer base plate and the reactor vessel lugs were examined following the incident (Ref. Work Order # 732708-01). The base plate was found deformed (i.e. – bent) downward at the 140°, the 220°, and the 320° locations. The 40° dryer location was not damaged. The base plate near the 140° guide slot location was bent down by ¾ inch, the 220° was bent down by 5/8 inch, and the 320° was bent down by 5/16 inch. The base plate near the 140° was bent on the right hand side, when looking at the dryer, and the other two locations were bent on the left hand side when looking at the dryer. This is shown schematically in Figure 1.

The videotape of the in vessel dryer support lug inspection was reviewed and stills extracted as shown in figures 1 through 12 below. The 40° lug (Figure 3) had a corner deformation on the right hand side of the lug, when looking at the lug from the vessel ID, even though the dryer base plate at this location was not damaged. The support lug located at 140° (Figure 4) also had a corner deformation on the right hand side of the lug, when looking at the lug from the vessel ID. The 220° (Figures 5 and 6) and 320° (Figures 7 and 8) support lugs were damaged on the lower left hand corner. The worst deformations were on the 220° and 140° location.

The design of the base plate cutouts and the dryer guide rod slot would allow the dryer to rotate and potentially allow the cutout gussets to impact the dryer support lugs. Based on the geometry of the vessel lugs and the base plate cutouts, it does not seem reasonable that the dryer would impact two lugs on the right side and the other two on the left side. This conclusion would lead to the possibility that there were two different impacts, or events. However, based on discussion with individuals who were present, there was only one impact event. That is, the dryer was not lowered or rotated and then lifted again. This leads to the possibility of multiple impacts during a single event.

The as-built elevation of the top of the dryer support lugs is excerpted from the reactor vessel as-built drawing (CBI drawing 69-4824) and is provided in Table 1.

Lug Azimuth Location	As-Built Elevation
40	616 - 13/16 "
140	617 – 1/32 "
220	616 – 11/16 "
320	616 – 13/16 "

Table 1

Dryer Support Lug As-Built Elevation
(Measured from the support skirt)

This drawing indicates that the lowest lug is the 220° lug, and the highest is the 140° lug. This assumes that they are all approximately the same length. The data indicates that the 220° lug is 11/32" (0.344") below the 140 degree lug. Also, the 40° and the 320° lugs are 7/32" (0.219") below the 140° lug.

As can be seen in figures 7 through 11, the lugs were also damaged when the dryer was lowered into the reactor vessel. This damage indicates that the combination of dryer support lug as-built location and size combined with the dryer base plate cutout as-built location and size, and the as-built clearances between the dryer guide pins and guide slots, resulted in a lack of clearance and interference between the dryer support lugs and the cutouts when lowering the load. Since a review of all of the as-built locations and sizes and combinations thereof is difficult and yields results that are subject to the stacking of multiple accuracies, it is sufficient t note that the potential for the interference exists based on the evidence of damage to the lugs from lowering the load.

A plausible sequence of events can be established using the evidence of damage to the dryer support lugs and the dryer base plate and the as-built elevations of the bottom of the dryer support lugs. It cannot be established that this is the exact sequence of events, but only that this is a likely scenario that is coincidental with the established facts.

Since the 220° dryer support lug is the lowest lug, it is presumed that the dryer base plate cutout contacted this lug first. (Note the contact point for all of the interferences would be the gusset plate that is located on the either side of the base plate cutout.) Also, since the dryer contacted the left side of the lug, the dryer is rotated clockwise when looking down from the crane. The initial impact on this lug is supported by the lower elevation and fact that the damage to the dryer support lug at his location was the worst for all of the support lugs (See figures 3 and 4). It is not necessarily supported by the amount of damage to the dryer base plate.

The dryer would continue to be lifted as it yielded both the support lug and the dryer base plate at the 200° location. Once the dryer had been lifted approximately 1/16", the dryer would contact the 320° location at the left hand side of the lug. The dryer also should have impacted the 40° lug on the left hand side, however it did not. This can be explained by reviewing figures 7 and 8.

Note that the damage to the 40° lug when lowering the load occurred on the right hand side of the lug. This indicates that when the dryer is positioned such that it passes by all of the lugs, it is closer to the right hand side of the 40° lug. Therefore, the largest clearance between the 40° dryer support lug and the dryer base plate cutout would be on the left hand side of the lug. Then, if the dryer is rotated clockwise, it may not impact the left hand side of the 40° lug since that is the side of the greatest clearance.

Once the dryer base plate contacts the 320° support lug, the load is shared between the base plate locations at 220° and 320°. This would help to limit the amount of base plate deformation at the 220° location. The dryer would continue to lift and possibly rotate such that the 220° to 320° section of the dryer would be lower than the 40° to 140° side.

The dryer released from the 220 and 320° lugs and swung, or tilted, while rotating back counter clockwise. During the tilt or swing, the dryer impacted the support lugs at 40 and 140 degrees. The release mechanism is supported by the edge displacement damage to the 320° lug, which makes it appear that the dryer slid laterally away from the lug, causing material on the lug to move downward (Figures 5 and 6). As stated previously, the dryer, once it was free to swing, impacted the lower right edge of both the 40 and 140° support lugs. The dryer impacted the lower part of the 140 degree support lug and impacted only the edge of the 40 degree lug. The reason the dryer impacted below the 140° support lug is due to the higher elevation of the lug and the tilting of the dryer. The dryer scraped the lower right hand side of the 40° vessel support lug (Figure 1) because that lug is slightly higher than the 140° support lug. That is, the dryer did not wedge under the 40° lug because of the lower elevation versus the 140° lug, but it did hit the edge of the lug, as seen in Figure 1.

Conclusions

Based on this evaluation, the following summarizes the interference event that occurred during the initial dryer installation:

1. Dryer base plate guide slots impact multiple dryer support lugs during the initial lowering into position.
2. Dryer base plate interferes with the separator guide pins and cannot be placed in final position. This causes the dryer to be lifted to facilitate modifications.
3. Dryer is rotated clockwise during the lift (slightly, less than 1 inch).
4. Dryer base plate guide slot gusset interferes with dryer support lug at the 220° location. This results in a ½” high by 3/8” wide damaged area in the dryer support lug and a 5/8 inch downward deflection of the base plate.
5. Dryer base plate guide slot gusset interferes with dryer support lug at the 320° location. This results in part of the dryer support lug being sheared off and the dryer base plate deflection of 5/16”.
6. Dryer tilts noticeably along the 0 and 180° axis, prior to releasing from the lugs.
7. Dryer releases, swinging back towards 220 and 320° location.

8. Dryer rotates and swings into the 140 and 40° lug.
9. Dryer impacts the 140° lug below the right lower edge of the lug.
10. This impact results in a sharp crease in the dryer support lug and the formation of an edge on the base plate gusset. The corner of the 140° lug is pushed in and partially shears off.
11. During the tilt/rotation, the dryer impacts the right bottom corner of the 40° lug, shearing off the corner.
12. The dryer lift is completed without further incident.

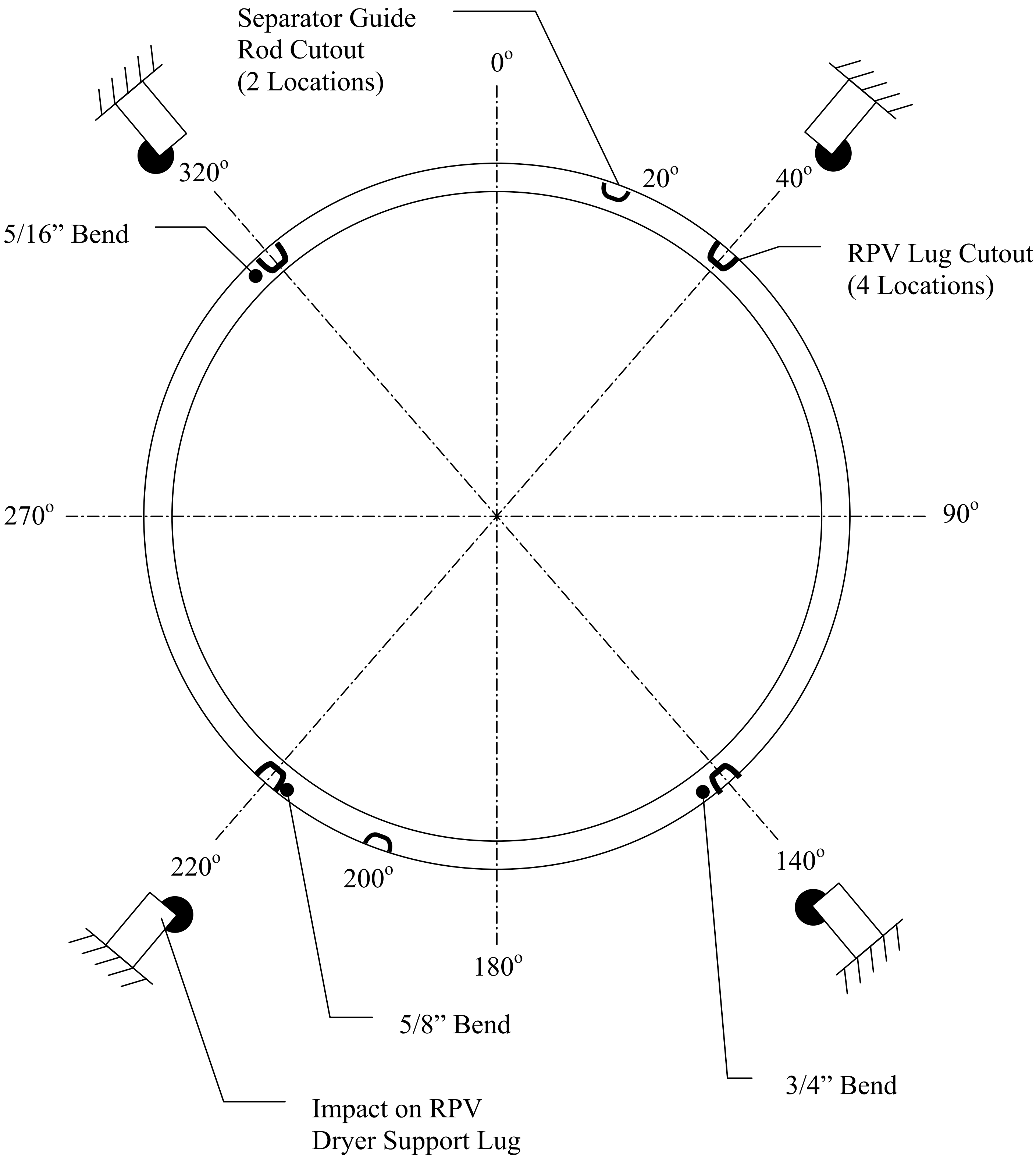


Figure 1
Steam Dryer Plan – Impact Locations

Att 7: Dryer to Dryer Lug Impact Analysis (Lifting Event)

Figure 2

General Relationship Between Dryer Cracking (Top), Dryer Guide Slot Cutout at 140 Degrees (Center), and Dryer Support Lug at 140 Degrees (Bottom)

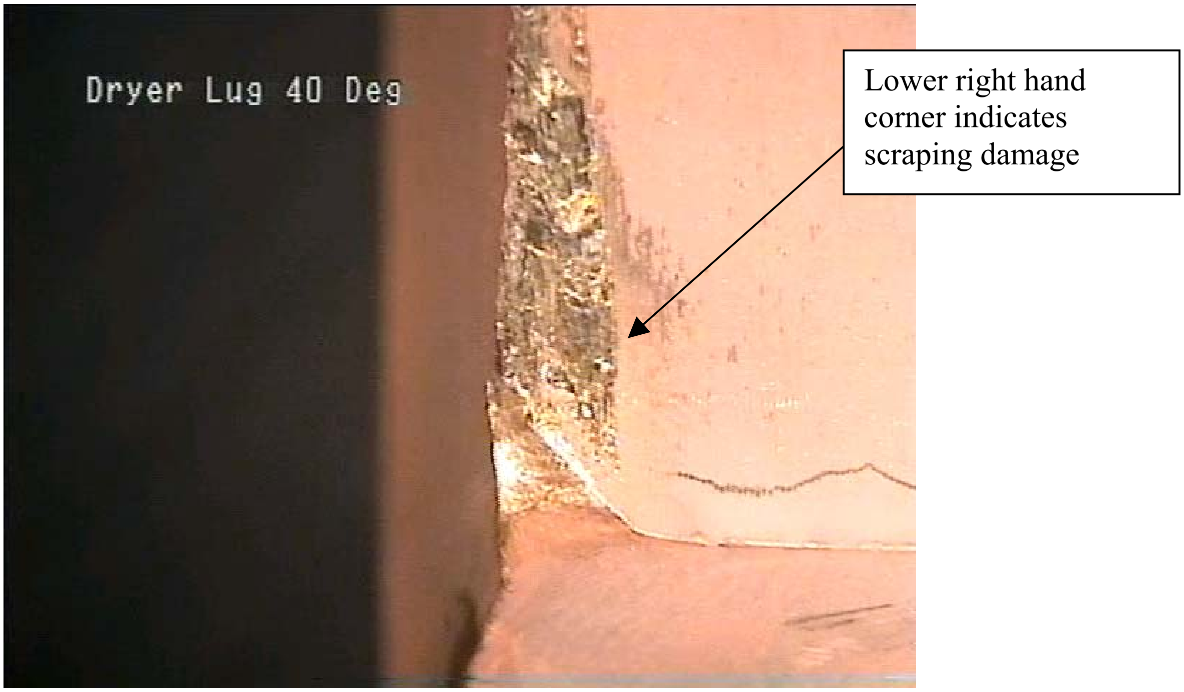


Figure 3

Damage to 40 Degree Lug, Lower Right Hand Corner Damaged During Impact

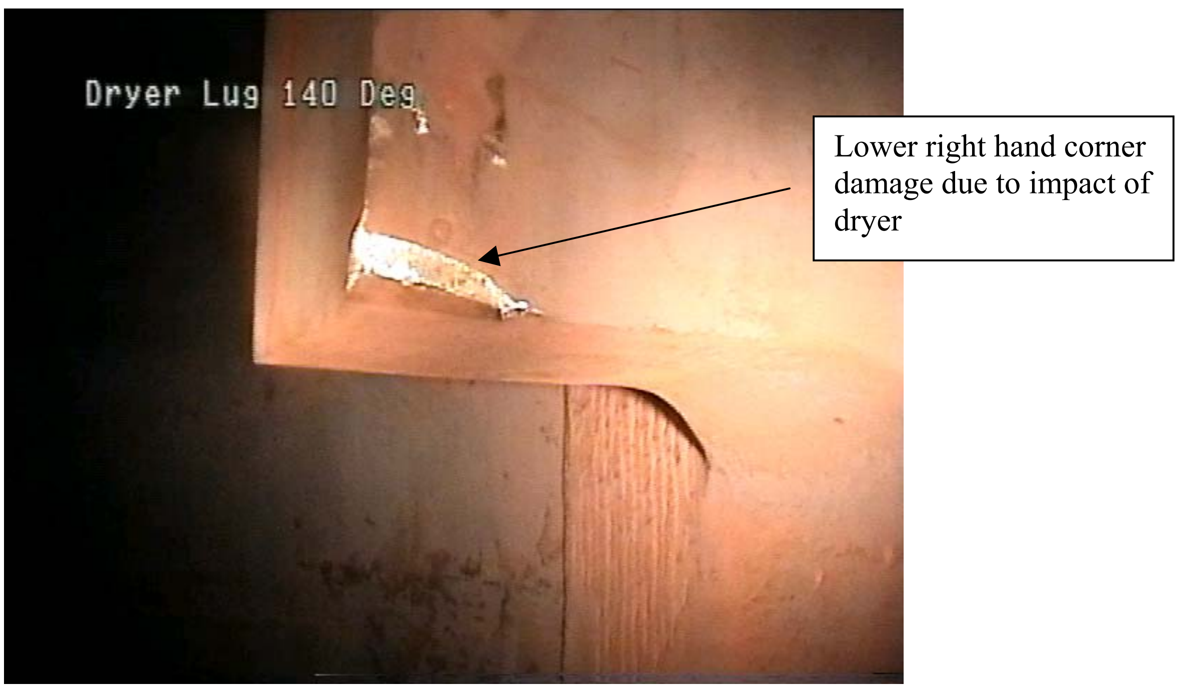


Figure 4

Damage To 140 Degree Lug, Lower Right Hand Corner Damaged Due to Major Impact

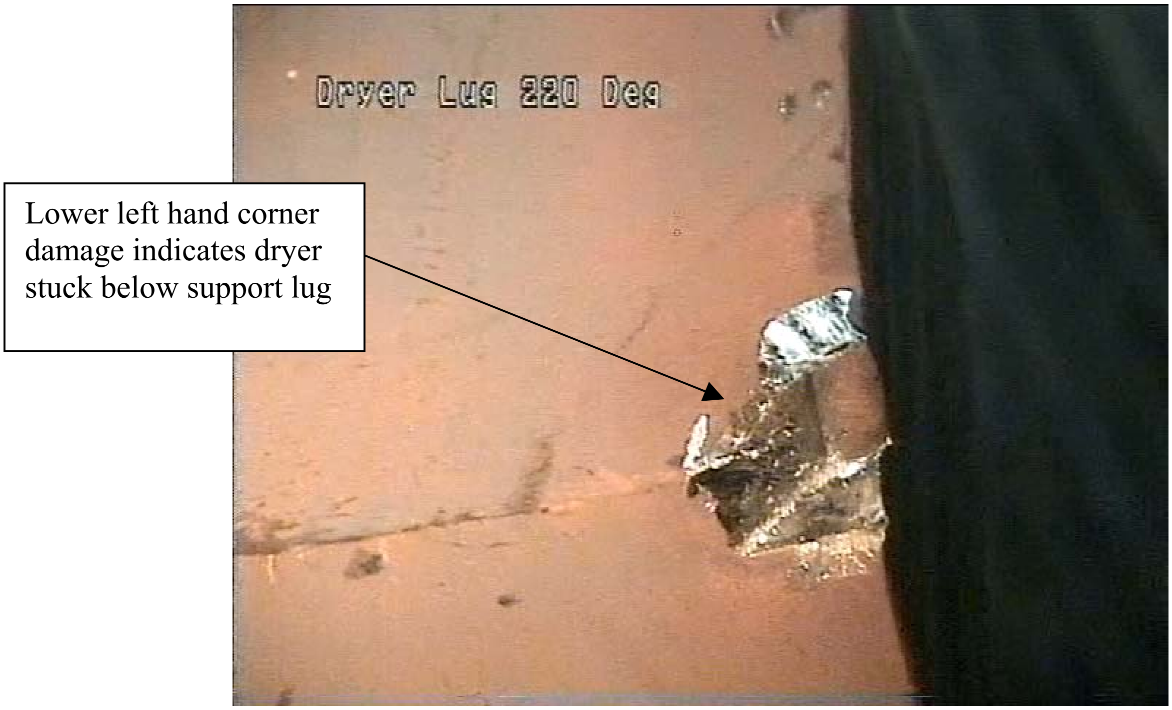


Figure 5

Damage To 220 Degree Lug, Lower left hand Corner

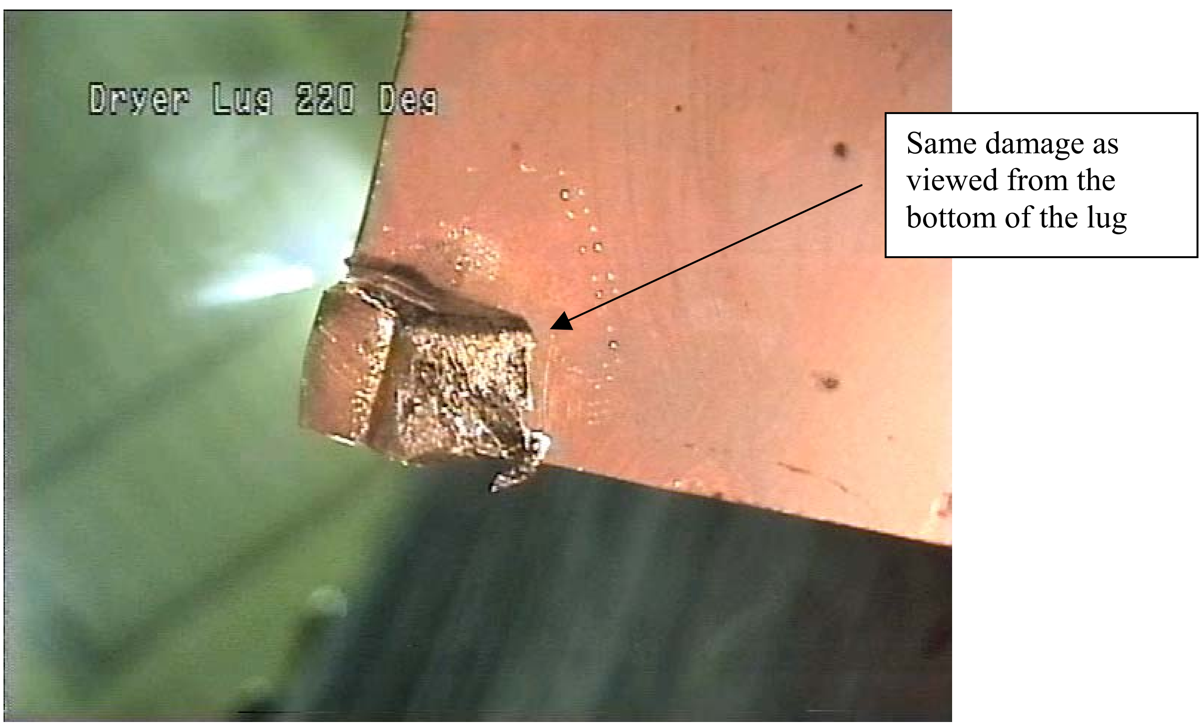


Figure 6

Damage To 220 Degree Lug, Lower left hand Corner (View from Bottom)

Damage to lower left hand corner due to dryer. Note some damage indication is from top to bottom.

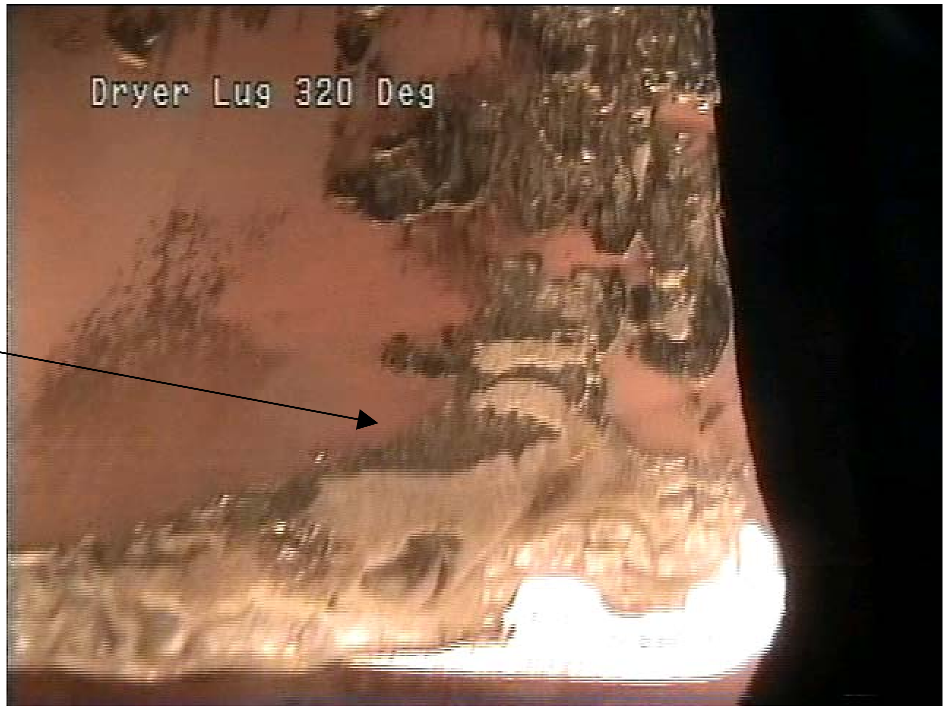


Figure 7

Damage to 320 Degree Lug, Lower Left Hand Corner

Same damage as previous figure, seen from the bottom of the lug.

Figure 8

Damage to 320 Degree Lug, Lower Left Hand Corner (View From Bottom)

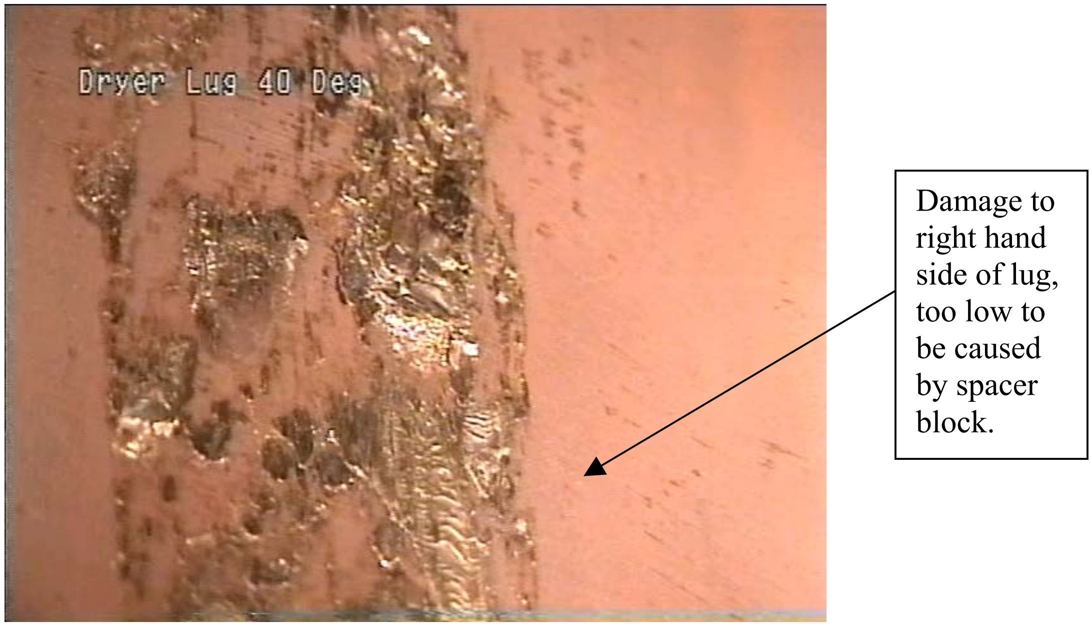


Figure 9

Damage to Right Hand Side of 40 Degree Lug, Due to Base Plate When Lowering

Att. 8: Q2R18 INR Resolution Matrix*

IR	INR Number	Current Rev	Title	Proposed Resolution (Not Final)	Resolution Document	EC
471848	Q2R18-IVVI-06-01	0	Steam Dryer Lifting Lugs at 45, 135, 225, &315 Deg	Repair Per FDDR RMCN08456	WO 681384-01, FDDR RMCN08456 Rev B	360356
472321	Q2R18-IVVI-06-02	0	Steam Dryer Skirt at 135 Deg	Repair Per FDDR RMCN08382	WO 681384-01, FDDR RMCN08382 Rev A	360356
474814	Q2R18-IVVI-06-03	3	Jet Pump 05 (WD-1)	JCO - Possibly replace Q2R19	GENE-0000-0052-9152 R0	360359
473034	Q2R18-IVVI-06-04	1	Steam Dryer SD-BE-V12-2H, SD-BE-V11-2H	Accept As Is	GENE-0000-0052-9728 R0	360356
475009	Q2R18-IVVI-06-05	0	Jet Pump 08 (WD-1)	JCO - Possibly replace Q2R19	GENE-0000-0052-9152 R0	360359
473344	Q2R18-IVVI-06-06	0	Steam Dryer Internal Weld SD-BF-V06-2H-ID	Accept As Is w/future inspection / LPA	GE-NE-0000-0052-7988-R0	360356
473619	Q2R18-IVVI-06-07	0	Steam Separator Upper Support Ring Gusset	Accept As Is w/future inspection	GENE-0000-0052-8398-R0	360359
473615	Q2R18-IVVI-06-08	0	Steam Dryer Internal Weld SD-BD-V06-2H-ID	Accept As Is w/future inspection / LPA	GE-NE-0000-0052-7988-R0	360356
473622	Q2R18-IVVI-06-09	1	Steam Separator Shroud Head Bolt 14 and 35	Rotate and perform VT-3	Video files 481701, 481101, 481301, 481401	360359
473626	Q2R18-IVVI-06-10	0	Steam Dryer Internal Weld SD-BB-V04-2H-ID	Accept As Is w/future inspection	GE-NE-0000-0052-7988-R0	360356
473923	Q2R18-IVVI-06-11	1	Steam Dryer Internal Debris	Accept As Is w/future inspection / LPA	Lost Parts Analysis EC 360467	360356
473871	Q2R18-IVVI-06-12	0	Steam Dryer Internal Area (Separator Guide Cutout)	Increase clearance FDDR RMCN088242	WO 681384-01, FDDR RMCN08242 Rev A	360356
473839	Q2R18-IVVI-06-13	0	Separator Lower Support Ring Gusset	Accept As Is w/future inspection	GENE-0000-0052-8398-R0	360359
474491	Q2R18-IVVI-06-14	0	Jet Pump 10 Wedge Assembly	Accept As Is w/future inspection	GENE-0000-0052-9152 R0	360359
474070	Q2R18-IVVI-06-15	0	Jet Pump 07 Wedge Assembly	Replace swing gate as planned	WO 823272-01	360359
473844	Q2R18-IVVI-06-16	0	Feedwater Sparger End Bracket	Planned Tack Weld per FDI 0194	GE-NE-0000-0052-8396-R0	360359
474064	Q2R18-IVVI-06-17	0	Shroud Repair Yoke at 290 Degrees	Accept As Is - Installed condition	GE-NE-0000-0052-8402-R0	360359
474485	Q2R18-IVVI-06-18	0	Dryer General Visual (220 to 320 Degrees)	NRI - No action required	IR 474497 comments	360356
474497	Q2R18-IVVI-06-19	0	Feedwater Sparger 13&16 Degree End Bracket & Pin	Planned Tack Weld per FDI 0194	GE-NE-0000-0052-8396-R0	360359
474501	Q2R18-IVVI-06-20	0	Steam Dryer Skirt Baseplate at 220 Degrees	Repair Per FDDR RMCN08242	WO 681384-01, FDDR RMCN08404 Rev A	360356
475003	Q2R18-IVVI-06-21	0	Steam Dryer WSL @ 220 Degrees	No Action Required - unchanged	IR 475003 comments	360356
475328	Q2R18-IVVI-06-22	0	CS Lower Elbow to Shroud Pipe 290 Degree Azimuth	Inspect next RFO	INR Exelon Level III review	360359
474514	Q2R18-IVVI-06-23	0	Steam Dryer Base Plate Distortion at 320 Degrees	No change- Accept As Is	EC 360356	360356
474517	Q2R18-IVVI-06-24	0	Steam Dryer Surface Anomalies at SD-SKT-V11-ID	NRI - No action required	IR 474517 comments	360356
474977	Q2R18-IVVI-06-25	0	Shroud Head Flange Ring Segment (EDM Hole)	Accept As Is - Previously eval'd	GENE-771-110-0595 R0	360359
475862	Q2R18-IVVI-06-26	0	Core Support Flange Ring OD	Accept As Is w/future inspection	GENE-771-110-0595 (May 1995)	360359
475332	Q2R18-IVVI-06-27	0	Shroud Head Flange Ring OD	Accept As Is	GENE-0000-0053-0964-R1	360359
475339	Q2R18-IVVI-06-28	1	Steam Dryer WSLs @ 40, 140 and 320 Degrees	No Action Required - unchanged	IR 475339 comments	360356
475369	Q2R18-IVVI-06-29	0	Steam Dryer Indication, SD-LB-03-W1 OD @ 220 De	Repair per FDDR RMCN08435	WO 681384-01, FDDR RMCN08435 Rev A	360356
476654	Q2R18-IVVI-06-30	0	RPV Jet Pump Annulus FME	Remove FME	Lost Parts Analysis EC 360467	360359
476657	Q2R18-IVVI-06-31	1	Steam Dryer Exit Plenum Perforated Plate	Accept As Is	GENE-0000-0053-0964-R0	360356
477326	Q2R18-IVVI-06-32	0	CS Sparger S3c Drain (two plugs missing tack welds)	Accept As Is	GENE-0000-0053-0964-R0	360359
N/A	Q2R18-IVVI-06-33	0	Tie Rod Loose and Missing Nuts (As designed)	NRI - No action required	INR - Future reference only. Mention in EC.	360359
476540	None - IR only		SHB #9 suspect based on UT criteria	Accept As Is w/future inspection	IR, GE Letter DRF B13-01903-8	360359

* The highlighted items are specifically included in the scope of RCR 472321

Att. 9: CA's to Address Programmatic/ Organizational Issues

A. CA's from ERV RCA (Ref. 38) aligned with Q2R18 Steam Dryer RCA CF. 2

Background: CF #3 to ERV RCA: Organizational effectiveness and decision-making.

Description: The organizational contributors taken in aggregate demonstrate weaknesses in managing information, over-reliance on contractor-performed analysis, and applying a systematic approach to decision making for complex high-risk situations.

Causes Being Addressed	Corrective Action (CA) or Action Item (ACIT))	Owner	Due Date
CF#3 Organizational effectiveness and decision-making.	Provide training to Corporate Engineering personnel on the requirement and application of OP-AA-106-101-1006 for complex decision-making (CA# 23 revises OP-AA-106-101-1006). Complex engineering decisions which involve historical data, repeat equipment failure, risk and complex analysis shall require the use of OP-AA-106-101-1006 Operational And Technical Decision Making Process. **CA #20**	A8081 TRLS	9/20/2006
CF#3 Organizational effectiveness and decision-making.	Provide training to Quad Cities Engineering personnel on the requirement and application of OP-AA-106-101-1006 for complex decision-making (CA# 23 revises OP-AA-106-101-1006). Complex engineering decisions which involve historical data, repeat equipment failure, risk and complex analysis shall require the use of OP-AA-106-101-1006 Operational And Technical Decision Making Process. **CA #21**	A8461 ESPT	9/02/2006
CF#3- from Ref. 38 Organizational effectiveness and decision-making.	Update HU-AA-1212 Technical Task Risk/Rigor Assessment, Pre-Job Brief, Independent Third Party Review, And Post-Job Brief to provide a link to OP-AA-101-1006 for complex engineering decisions and/or products which involve historical data, repeat equipment failure, risk and complex analysis. **CA #22**	A8053VP BWR (BRWRD)	6/16/2006
CF#3- from Ref. 38 Organizational effectiveness and decision-making.	Training CRCs shall evaluate the need of providing training to Exelon FLSs and above on the use and application of OP-AA-106-101-1006. **ACIT #4**	A8068EN DES	6/16/2006
CF#3- from Ref. 38 Organizational effectiveness and decision-making.	Submit update to OP-AA-106-101-1006 Operational And Technical Decision Making Process Attachment B, "Recognize Conditions" to include lessons learned from the ERV root cause and documentation of all personnel involved in the final product. Closure to include new assignment for processing of procedure change to Operations peer group. **CA #23**	A8068EN DES	6/30/2006

Att. 9: CA's to Address Programmatic/ Organizational Issues

B. CA's from ERV Actuator RCA (Ref. 38) & Replacement Dryer Fuel Impacts RCA (Ref. 37) aligned with Q2R18 Steam Dryer RCA – "Negative Design Impacts "

Causes Being Addressed	Corrective Action (CA) or Action Item (ACIT))	Owner	Due Date
CF#3 – from Ref. 38 Organizational effectiveness and decision-making.	Change the design input requirements to include upfront challenges to analysis and assumptions as part of the design review. The documents include CC-AA-103-1003 Owner's Acceptance Review Of External Configuration Change Packages and CC-AA-309 Control of Design Analysis. These front-end challenges shall be applied to all design changes and modifications independent of level. **CA #25**	A8068ENDES	7/28/2006
CAPR3 – from Ref. 37	Revise HU-AA-1212, "Technical Task Risk/Rigor Assessment…" to include guidance on how to select what type of third-party review(s) are required. AT#: 330331-21 (complete)	Revision issued by NCS.	complete
CAPR4– from Ref. 37	Revise PC-AA-1008, "Issue Chartering". Add step 4.3.3.2 to require project teams – in the project scoping phase - to review all CC-AA-102 attachments in order to determine scope additions and affected organizations. AT#: 281476-07	NCS A8070PM	08/31/06
ACIT6– from Ref. 37	Evaluate the results of this root cause investigation for inclusion in the Project Management TAC. Specifically, investigate training project managers on how to identify which departments to include on a project and when. AT#: 330331-22	NCS A8070PM	Complete

ATTACHMENT 14 – of LS-AA-125-1001 (ATT. 10 of specific RCA 472321)

Root Cause Report Quality Checklist
Page 1 of 2

A. Critical Content Attributes	YES	NO
1. Is the condition that requires resolution adequately and accurately identified?	X	
2. Are inappropriate actions and equipment failures (causal factors) identified?	X	
3. Are the causes accurately identified, including root causes and contributing causes?	X	
4. Are there corrective actions to prevent recurrence identified for each root cause and do they tie DIRECTLY to the root cause? AND, are there corrective actions for contributing cause and do they tie DIRECTLY to the contributing cause?	X	
5. Have the root cause analysis techniques been appropriately used and documented?	X	
6. Was an Event and Causal Factors Chart properly prepared?	X	
7. Does the report adequately and accurately address the extent of condition in accordance with the guidance provided in Attachment 3 of LS-AA-125-1003, Reference 4.3?	X	
8. Does the report adequately and accurately address plant specific risk consequences?	X	
9. Does the report adequately and accurately address programmatic and organizational issues?	X	
10. Have previous similar events been evaluated? Has an Operating Experience database search been performed to determine whether the problem was preventable if industry experience had been adequately implemented?	X	
B. Important Content Attributes		
1. Are all of the important facts included in the report?	X	
2. Does the report explain the logic used to arrive at the conclusions?	X	
3. If appropriate, does the report explain what root causes were considered, but eliminated from further consideration and the bases for their elimination from consideration?	X	
4. Does the report identify contributing causes, if applicable?	X	
5. Is it clear what conditions the corrective actions are intended to create?	X	
6. Are there unnecessary corrective actions that do not address the root causes or contributing causes?	**X**	
7. Is the timing for completion of each corrective action commensurate with the importance or risk associated with the issue?	**X**	

ATTACHMENT 14
Root Cause Report Quality Checklist

C. Miscellaneous Items	YES	NO
1. Did an individual who is qualified in Root Cause Analysis prepare the report?	X	
2. Does the Executive Summary adequately and accurately describe the significance of the event, the event sequence, root causes, corrective actions, reportability, and previous events?	X	
3. Do the corrective actions include an effectiveness review for corrective actions to prevent recurrence?	X	
4. Were **ALL** corrective actions entered and verified to be in Action Tracking?		*
5. Are the format, composition, and rhetoric acceptable (grammar, typographical errors, spelling, acronyms, etc.)?	x	

* New AT items are created by CAP organization after MRC approval of RCA.