August 7, 2003

Mr. John L. Skolds, President
Exelon Nuclear
Exelon Generation Company, LLC
Quad Cities Nuclear Power Station
4300 Winfield Road
Warrenville, IL 60555

SUBJECT: QUAD CITIES NUCLEAR POWER STATION, UNIT 2
NRC SPECIAL INSPECTION REPORT 50-265/03-11

Dear Mr. Skolds:

On June 26, 2003, the U. S. Nuclear Regulatory Commission (NRC) completed a special team inspection at your Quad Cities Nuclear Power Station, Unit 2. The enclosed report documents the inspection findings which were discussed with Mr. Tulon and other members of your staff on June 26, 2003.

On May 6, 2003, increased moisture carryover was noted on Quad Cities Unit 2. By May 28, 2003, moisture carryover had increased to more than .35%. Operators reduced reactor power and moisture carryover dropped. On June 10, 2003, Quad Cities Unit 2 commenced shutdown to inspect and repair the cause of the increased moisture carryover. Inspections revealed that a steam dryer outer bank hood had experienced significant cracking near the steam line nozzles, internal braces were broken, and three tie bars were cracked. This failure was of increased interest because it represented the second apparent vibration induced dryer failure on Unit 2 since operation at Extended Power Uprate power levels began in March 2002. Based on the criteria specified in Management Directive 8.3 and Inspection Procedure 71153, a Special Inspection was initiated in accordance with Inspection Procedure 93812 and Regional Procedure RP-1219. The Special Inspection evaluated the facts, potential significance, and your resolution of this issue.

The root cause determination for the steam dryer hood failures, and assessment of the extent of condition potentially affecting other parts of the dryer assembly, were not complete at the time of the special inspection. Further work was ongoing, including metallurgical examination of the failed material samples removed from the dryer hood to further identify the failure mechanism. Further analytical work was also proceeding, including flow analysis and evaluation of flow testing options to provide more complete understanding of the complexities of the flow-induced vibratory loadings affecting the steam dryer under EPU conditions.

Our review of the computational fluid dynamics analysis and finite element model along with the similarities in appearance of the fracture surface between the current failure and the cover plate failure in July 2002, supports your belief that the failure mechanism was flow induced high cycle fatigue. The inspectors concluded that the modified dryer, including the 1" thick replacement plates and the flow straightening gussets will reduce stresses to an acceptable level. The repairs to the upper dryer hood appear to be structurally adequate to preclude recurrence of fatigue-type cracking in the modified hood structure at least for the remainder of the current fuel cycle.

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Sincerely,

/ RA /

Geoffrey E. Grant, Director
Division of Reactor Projects

Docket Nos. 50-265
License Nos. DPR-30

Enclosure: Inspection Report 50-265/03-11

cc w/encl: Site Vice President - Quad Cities Nuclear Power Station
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U.S. NUCLEAR REGULATORY COMMISSION

REGION III

Docket Nos:	50-265
License Nos:	DPR-30
Report No:	50-265/03-11
Licensee:	Exelon Nuclear
Facility:	Quad Cities Nuclear Power Station, Unit 2
Location:	22710 206th Avenue North Cordova, IL 61242
Dates:	June 23 through June 26, 2003
Inspectors:	J. Jacobson, Team Lead K. Stoedter, Assistant Team Lead T. Bilik, Engineering Inspector P. Sekerak, Mechanical Engineer, NRR C. Wu, Mechanical Engineer, NRR
Approved by:	Mark Ring, Chief Branch 1 Division of Reactor Projects

Enclosure

SUMMARY OF FINDINGS

IR 05000265/2003-011; Exelon Nuclear; on 6/23/03-6/26/03, Quad Cities Nuclear Power Station; Unit 2. Special Inspection for steam dryer failure.

This special inspection examined the facts and circumstances surrounding a Unit 2 steam dryer failure which was identified following shutdown on June 11, 2003. The inspection was conducted by Region III inspectors and engineering specialists from NRR. No findings were identified. The NRC's program for overseeing the safe operation of commercial nuclear power reactors is described in NUREG-1649, "Reactor Oversight Process," Revision 3, dated July 2000.

REPORT DETAILS

Background and Overview

The steam dryer assembly is fabricated from ASTM A-240 Type 304 stainless steel and is mounted in the reactor vessel above the steam separator assembly, latched to brackets in four places on the inside of the vessel wall below the steam outlet nozzles. It forms the top and sides of the wet steam plenum, and provides a seal between the wet steam plenum and the dry steam flowing from the top head area and out the steam nozzles. Wet steam flows upward and outward through the dryers. Moisture is removed by impinging on the dryer vanes and flows down through drains to the reactor water in the downcomer annulus below the steam separators. The steam dryer does not perform a safety function and is not required to prevent or mitigate the consequences of accidents. Although the steam dryer is not a safety related component, the assembly is designed to withstand design basis events without the generation of loose parts and the dryer is expected to maintain structural integrity.

On May 6, 2003, increased moisture carryover was noted on Quad Cities Unit 2. By May 28, 2003, moisture carryover had increased to more than .35%. Operators reduced reactor power to levels prior to the extended power uprate and moisture carryover dropped. On June 10, 2003, Quad Cities Unit 2 commenced shutdown to inspect and repair the cause of the increased moisture carryover. Inspections revealed that a steam dryer outer hood failed through-wall near the steam line nozzles, internal braces were broken, and three tie bars were cracked. Attachment 2 to this report contains drawings and pictures of the dryer and the damage.

Details of the damage, the root cause evaluation, and the planned repairs were discussed with the NRC staff during conference calls on June 17, 18 and 20, 2003. Among the outcomes of these discussions was a decision to conduct a special inspection of the licensee's efforts to identify the cause of the steam dryer failure and to assess the structural adequacy of the repair of the damaged areas of the steam dryer. The special inspection team consisted of NRC Region III personnel who coordinated and led the team activities, and Office of Nuclear Reactor Regulation, Division of Engineering (NRR/DE) personnel who provided specialized technical assistance for review of the analytical and engineering details of the damage assessment and repair.

4. OTHER ACTIVITIES

4OA3 Event Follow Up

.1 Sequence of Events (93812)

a. Inspection Scope

The inspectors reviewed operator and chemistry logs, moisture carryover sampling results, and other documentation; interviewed licensee personnel; and developed the following sequence of events for both the June 2002 and June 2003 steam dryer failures:

Date	Event Description
1999-2001	Historically, the Quad Cities Unit 2 steam dryer operated at moisture carryover levels of approximately .20 percent or lower. Visual inspections to assess the dryer's material condition were not required during this time frame. Since visual inspections were not required, the inspectors were unable to determine if the Unit 2 steam dryer was experiencing cracking prior to Extended Power Uprate (EPU) implementation.
12/21/01	The Nuclear Regulatory Commission approved Exelon Nuclear's EPU plan. This plan described the activities required and the acceptability of increasing the electrical generation of Quad Cities Units 1 and 2 by 17.8 percent.
02/12/02	Operations personnel shut down Unit 2 for a refueling outage and EPU implementation. The licensee conducted visual examinations of the dryer hold down assemblies and tie bars as the dryer was removed from the reactor vessel. No recordable indications were identified. During the refueling outage, 22 perforated plates were installed on the steam dryer to improve the dryer's moisture removal capabilities.
03/05/02	Operations personnel synchronized Unit 2 to the electrical grid.
03/06-14/02	The licensee conducted power ascension testing.
03/14/02	Unit 2 achieved a new maximum power level of 912 MW_e or 95.8 percent of the new licensed power level. Chemistry personnel began taking weekly moisture carryover samples. Moisture carryover remained stable at approximately .03 percent.
05/22/02	Chemistry personnel transitioned to monthly moisture carryover samples.
06/08/02	Unit 2 began experiencing unexpected changes in reactor power, pressure, level, and main steam line flow. Moisture carryover increased to .30 percent. The licensee determined that moisture carryover was likely increasing due to steam dryer degradation.
06/11-19/02	Chemistry personnel performed moisture carryover sampling once per day and as requested by the operations department. Moisture carryover remained at approximately .30 percent.
06/18/02	Moisture carryover increased to .40 percent. Unit 2 experienced additional changes in reactor power, pressure, level, and main steam line flow.

06/20/02	Moisture carryover increased to .74 percent. Unit 2 experienced additional changes in reactor power, pressure, level, and main steam line flow. The licensee reduced Unit 2 reactor power to pre-EPU levels (approximately 805 MW_e or 2511 MW_{th}). Chemistry personnel conducted moisture carryover sampling once per shift.
06/21-07/10/02	Moisture carryover stabilized at approximately .30 percent due to the drop in reactor power. On July 7, the main steam line leakage alarm annunciated and cleared. Two days later, the alarm annunciated and did not clear. Moisture carryover peaked at .44 percent following receipt of the alarms.
07/11/02	The licensee identified large differences in main steam line flow which were subsequently found to be caused by dryer fragments entering one or more of the main steam lines. Operations personnel entered Technical Specification 3.0.3 since the operability of safety-related systems could no longer be assured. Unit 2 was shut down later the same day.
07/13/02	The licensee inspected the steam dryer components using VT-1 and VT-3 techniques. The results of the inspection showed that the changes in moisture carryover and reactor operating parameters were caused by the failure of a ¼ inch thick steam dryer cover plate. Cover plate fragments were found in a main steam line flow venturi and a turbine stop valve inlet screen. Engineering personnel conducted a detailed examination of the broken cover plate and determined that the plate failed due to high cycle fatigue caused by flow induced vibrations. The licensee believed that the flow induced vibrations were caused by an increase in steam flow within the reactor vessel (the increased steam flow was expected as part of the EPU). The frequency of the flow induced vibration coincided with the natural frequency of the cover plate which created a resonant condition. The licensee repaired the dryer by replacing the ¼ inch thick cover plate with a ½ inch thick cover plate. The identical cover plate on the opposite side of the dryer was also replaced with the ½ inch plate as a precaution. The use of thicker cover plates changed the natural frequency of the plates such that a resonance condition no longer existed in this area of the dryer.
07/21/02	Operations personnel synchronized Unit 2 with the electrical grid following the steam dryer repairs. Chemistry personnel conducted moisture carryover sampling once per shift.
07/23/02	Unit 2 returned to EPU power levels.

07/26-28/02	Chemistry personnel conducted moisture carryover sampling on a daily basis. Moisture carryover stabilized at approximately .03 percent.
07/29/02 - 02/20/03	Chemistry personnel conducted moisture carryover sampling on a weekly basis. Moisture carryover remained at .03 percent.
02/20 - 04/15/03	Chemistry personnel conducted moisture carryover sampling on a monthly basis. No changes in moisture carryover were noted.
04/16/03	Moisture carryover increased slightly from .03 to .05 percent. At 1:22 p.m., the 3B power operated relief valve unexpectedly opened and failed to close. Operations personnel initiated a manual reactor scram due to increasing torus water temperature. Unit 2 remained shut down to repair the power operated relief valve.
04/20/03	Operations personnel synchronized Unit 2 with the electrical grid.
04/21/03	Unit 2 commenced operation at the EPU power levels.
05/01/03	Chemistry personnel identified a possible increase in moisture carryover from .05 percent to .317 percent during routine sampling. The chemistry department subsequently determined that the moisture carryover results were abnormally high due to the presence of Antimony-124 in the carryover sample. The licensee concluded that the Antimony-124 entered the moisture carryover sample stream due to the introduction of activated corrosion products following the April 16 manual reactor scram. The chemistry department assumed that moisture carryover results would continue to decrease as the amount of Antimony-124 was purged from the sample stream.
05/02/03	Chemistry personnel obtained an additional moisture carryover sample. The results of the analysis showed that moisture carryover levels were approximately .16 percent.
05/04/03	Moisture carryover increased to .17 percent.
05/06/03	Moisture carryover increased to .18 percent.
05/08/03	Operations personnel shut down Unit 2 to repair multiple power operated relief valves. Prior to the shut down, moisture carryover levels peaked at approximately .20 percent.
05/09/03	Engineering personnel initiated Condition Report No. 158145 due to the increasing trend in moisture carryover. Corrective actions for this condition report included developing a moisture carryover power ascension plan, completing an operability evaluation on the

	steam dryer, and inspecting the dryer during the next outage of sufficient duration.
05/10/03	Operations personnel synchronized Unit 2 with the electrical grid. Engineering personnel completed the operability determination for the Unit 2 steam dryer. The operability determination implemented a compensatory action to reduce Unit 2 reactor power to 2511 MW_{th} or below when moisture carryover was confirmed to exceed .35 percent.
05/11/03	Unit 2 commenced operation at EPU power levels.
05/16-23/03	Chemistry personnel conducted moisture carryover sampling on a daily basis. Moisture carryover levels fluctuated between .19 and .30 percent.
05/23-28/03	Operations personnel performed flux suppression testing to identify the location of a leaking fuel bundle. Chemistry personnel conducted moisture carryover sampling when requested.
05/28/03	Chemistry personnel increased the frequency of moisture carryover sampling to once per shift due to exceeding the pre-established limit of .35 percent. A second sample confirmed that moisture carryover had increased to .41 percent. Operations personnel initiated and completed actions to reduce Unit 2 reactor power to less than or equal to 2511 MWth.
05/29 - 6/10/03	Daily moisture carryover samples determined that carryover levels had stabilized to approximately .20 percent due to the decrease in reactor power.
06/11/03	Operations personnel shut down Unit 2 due to continuing degradation of the steam dryer.
06/12/03	The licensee conducted a visual inspection of the dryer and identified a 9’ long by 3-4" wide crack within the base metal of one of the top outer dryer hoods. The crack propagated in three directions and traveled through the weld into the vertical hood plate. No cracking was present in the part of the dryer that was repaired in June 2002. However, this new cracking was located on the same side of the dryer that was damaged previously. Engineering personnel initiated Condition Report No. 162964 to document the condition of the dryer.
06/13-26/03	The licensee conducted repairs on the steam dryer. The damage was attributed to flow induced vibration.
06/28/03	Unit 2 reached criticality and continued power ascension activities.

b. Findings

The failure represented the second dryer failure caused by vibration apparently associated with EPU operation.

.2 Review of Steam Dryer Operability Evaluation (93812)

a. Inspection Scope

The inspectors reviewed the technical adequacy of Operability Evaluation 158145-08 dated May 30, 2003, against the information provided in the Technical Specifications, the Updated Final Safety Analysis Report, and other design information; determined whether compensatory actions, if needed, were taken; and determined whether the evaluation was consistent with the guidance provided in LS-AA-105, “Operability Determination Process.” Multiple site and corporate engineering representatives were interviewed to better understand the engineering judgement documented in the operability evaluation. The inspectors also reviewed the Failure Modes and Effects evaluation performed by GE.

b. Findings

While the steam dryer was damaged, the damage did not result in the generation of loose parts which could have challenged safety system operation. The potential consequence of loose part generation was evaluated by GE and determined to be low. The Operability Evaluation was considered acceptable; however, the inspectors identified several instances where the information used to support continued steam dryer operability was incomplete. For example:

- Section 2.1 of the operability evaluation stated that operation of the automatic depressurization system (ADS) valves would not be impacted by the increased moisture carryover as long as the dryer remained intact. While this may be true, the licensee failed to consider the possibility of the dryer generating a loose part during a design basis accident. In addition, the licensee failed to address the continued ability of the ADS system to perform its safety function if the loose part was to become lodged in a steam line or one of the ADS valves.

- Section 2.3 of the operability evaluation required licensee personnel to document the basis for continued steam dryer operability. The lost parts analysis documented in this section stated that a dryer failure which resulted in relatively large pieces of dryer material entering a main steam line was not expected due to the structural improvements made to the dryer cover plate in June 2002. This statement was based on the belief that the failure mechanism occurring in the dryer was the same, or similar to, what was observed in June 2002. The possibility that a different type of failure mechanism may be occurring, and that the continued dryer degradation may create large loose parts which could impact safety systems, was not considered by the operability evaluation preparer or reviewer. Conversely, the licensee’s corporate engineering personnel indicated that they believed a new failure mechanism may be occurring and that the possibility of generating loose parts increased as moisture carryover increased and the dryer continued to degrade. The inspectors determined that the differences in logic between the site engineers and corporate engineers was not explored prior to the inspection even though numerous discussions were held between the involved individuals prior to approving the operability evaluation.

- Section 2.2 of the operability evaluation stated that the potential for dryer failure was time dependent based upon the rate of change in moisture carryover. The inspectors reviewed the licensee's compensatory actions implemented as part of the operability determination. Compensatory Action #1 required the licensee to create a guidance document which delineated the actions required once moisture carryover exceeded .35 percent. A corresponding limitation on the moisture carryover rate of change was not specified. Responsible licensee personnel informed the inspectors that this type of information would be considered for inclusion into a temporary procedure to monitor Unit 2 dryer performance.

The GE Failure Modes and Effects evaluation was a qualitative analysis performed utilizing an expert panel. The evaluation considered 37 dryer components and determined their relative probability of failure, consequence of failure, and relative detectability of failure during operation. The results concluded that the risk associated with the potential failures was low. While the evaluation was not considered rigorous, the results were deemed reasonable.

.3 Review of Current and Previous Failure Information (93812)

a. Inspection Scope

The inspectors reviewed selected portions of the current dryer video inspections conducted during June 12 through June 14, 2003 as well as those inspections conducted July 13, 2002 in support of the previous dryer cover plate failure. The purpose of this review was to evaluate the similarities between the failures. BWTX Report No. 1211-106-02-44, "Analysis of Steam Dryer Support Plate Coupons from Quad Cities," dated August 2002 was also reviewed to provide potential insights into the current failure mechanism. Finally, GE Report RPT-VISD-Q2-MJBD1, "Visual Inspection of the Steam Dryer," dated June 2003 was reviewed to evaluate the extent of the current failure. The inspectors were also given an audio-visual presentation by GE personnel which included an overall, detailed description of the current dryer hood failures, engineering basis for repairs, and also included a brief summary of the analysis of the previous failures which occurred at the dryer lower cover plates.

b. Findings

The steam dryer examinations were performed as VT-1 and/or VT-3 (both with 1/32 inch line resolution utilizing a color closed circuit television system. The inspectors reviewed GE Inspection Procedure GE-VT-203, Version 5, "Procedure for In Vessel Visual Inspection (IVVI) of BWR 3 RPV Internals" and found it acceptable for this application. IVVI Level II personnel performed the examinations from the refueling platform or auxiliary platform. Review of the examinations was performed by Level III personnel. NRC review of the video of the visual inspection conducted June 12 through 14, 2003 and the GE inspection report referenced above, identified that the top of the outer hood on the 90° side was fractured horizontally with transverse cracking running down the vertical face of the outer bank. Examination of the interior of the dryer hood identified that both diagonal braces had failed and were separated. Additionally, the vertical brace on the 180° side of the dryer had also failed. The three missing brace pieces were recovered from the vessel. During examinations of the top portion of the dryer, three tie bars were found to have cracks. Review of the inspection video from the previous cover plate failure in July 2002 identified that the cracking appeared similar in nature. The fracture surfaces from both the previous and current failures appeared smooth and flat, consistent with high-cycle fatigue. The visual evidence of the damaged areas also supported the GE theory that the most likely location of crack initiation occurred on the inside surfaces of the upper dryer hoods at the welds fastening the diagonal brace attachment gusset plates to the inside surfaces of the ½" thick hood plates at both the 90° and 270° hood locations.

Review of the August 2002 BWTX report referenced previously indicated that the previous cover plate failure was due to high cycle fatigue. Visual and electron microscopy examinations on the failure samples revealed no evidence of distinct changes in fracture appearance, or periods of arrestment, indicative of steady state crack propagation. The lack of macro and micro ductility indicated that crack propagation occurred steadily over a period of time and not due to a mechanical overload. Intergranular cracking and ductile tearing was not evident. Energy dispersive spectrometry examinations confirmed that the samples were consistent with Type 304 stainless steel. Due to the similarity of the crack appearance on the video from both the present and 2002 failures, the inspectors concluded that the cracking currently observed was most likely also due to high cycle fatigue.

The information provided by GE personnel regarding the analysis of the previous lower cover plate failure in July 2002, indicated that the analysis was limited to the immediate area of the failure, and did not include an extensive finite element model of the entire dryer structure. The localized failure of the cover plate was attributed to high cycle fatigue caused by resonant response of the high frequency (180 cycles / sec. range), flow-induced acoustic vibrations coincident with the natural frequency of the dryer cover plate. Further stress analysis and investigation of the potential effects of this loading, or other flow-induced resonant conditions at different frequencies, on other parts of the Quad Cities Nuclear Power Station (QCNPS), Unit 2 dryer assembly were not pursued in detail at that time.

.4 <u>Review of Flow Testing</u>

a. <u>Inspection Scope</u>

The inspectors reviewed flow test data as it applied to the evaluation of the QCNPS, Unit 2 dryer failure including the GE Nuclear Energy (GENE) Dryer Test Design Review Presentation, and in-plant measured data from other boiling water reactor (BWR) plants. The inspectors also met with Exelon and GE personnel to facilitate understanding of the details of high frequency acoustic flow characteristics, modeling, locations of recorded measurements, and applicability of these data to the QCNPS, Unit 2 dryer failure analysis.

b. Findings

The inspectors verified that peak frequencies associated with acoustical phenomena, based on the scale model testing results for QCNPS, Unit 2, are within the range of 130 to 230 cycles/second (Hz). Although the QCNPS, Unit 2 scale-model testing was not designed to identify peaks in the low frequency (<50 Hz) range, the inspectors found that in-plant test data from instrumented dryers at other BWR plants show prominent peaks occurring both within the range of 130 to 230 Hz, and in the low frequency range below 50 Hz. Therefore, low frequency (<50 Hz) flow-induced loads may exist at QCNPS, Unit 2, although the exact forcing function has not been characterized at this time. The pressure values in other frequency ranges were verified to be small and negligible.

The inspectors noted that the scale model testing focused on prediction of acoustic loads, and that the model was intended to be applicable only for acoustic flow phenomena, which was identified as the root cause of the previous dryer cover plate failure. The inspectors verified that acoustic resonant frequencies and amplitudes are sensitive to plant specific parameters. The inspectors examined test results showing that small variations in steam line configuration will change the amplitude and shift the resonant frequencies. Therefore, the flow test cannot predict the excited frequencies, or the amplitudes of excited resonance. Nevertheless, the potential resonant frequencies identified from the testing should be avoided and accounted for in the analytical basis for structural integrity of dryer modifications. Acoustic resonant phenomena have almost no damping, so when resonance occurs, amplitudes could become very large. The inspectors verified that finite element analysis techniques, utilizing the QCNPS, Unit 2 plant geometry, were used to design the steam dryer hood repair modifications such that the natural frequencies of vulnerable components are separated from the high frequency acoustic range loadings.

In assessing the generic application of the flow testing results, the inspectors noted that only a square dryer hood configuration, similar to the QCNPS, Unit 2 design, was tested. Dryer designs having hoods with stepped or curved configurations may have a different frequency range response to acoustic flow loading. Because of sensitivities due to test configuration variables, the flow tests for a square dryer hood configuration might not be applicable to other dryer configurations, and, thus, it would be inappropriate to use these flow tests to develop a plant specific forcing function for input to structural analyses for other plants with different dryer configurations. For use in future power uprate evaluations, flow testing techniques would need to be further developed to be used for generating a plant specific fluid forcing function which could be applied to predictive/preventative dryer modifications.

.5 Review of QCNPS Dryer Analysis

a. Inspection Scope

The inspectors reviewed documentation used for developing the dryer service loads and the associated finite element analysis model. These documents included GE stress analysis reports, GE design drawings, the computational fluid dynamics (CFD) analysis, computer codes used, the analysis assumptions, boundary conditions, loads and load combinations. The inspectors also met with Exelon and GE personnel to facilitate understanding of the details of the finite element modeling, analytical methodology, the analysis benchmarking process, and the QCNPS, Unit 2 dryer failure evaluation.

b. Findings

The inspectors verified the development of service loads and load combinations applied to the QCNPS, Unit 2 dryer failure analysis. The source of loadings considered in the evaluation included power operated relief valve (PORV) transient loads, degraded dryer operation with cracked cover plates, high frequency range acoustic loading, low frequency fluid instability (vortex) loading, bi-stable flow at the main steam exit nozzles, and the dryer support ring vertical motion.

Based on discussion with GE personnel, peak pressures from the PORV transient occurred at frequencies less than 10 Hz with a peak pressure differential less than 0.1 psi, which is considered to be small in comparison with the pressure differential from the CFD analysis. For bi-stable flow and acoustic loads, a flat pressure spectrum of 1 pound per square inch (psi) over the range of 130 to 200 Hz is applied in the ANSYS computer code finite element analysis. The inspectors verified that the use of a flat pressure spectrum in the high frequency range is consistent with the acoustic modeling test data for the QCNPS, Unit 2 dryer failure. There was no final documentation available at the time of inspection for bi-stable flow, PORV transient loads, or dryer support ring motion loading. The inspectors also found, based on discussion with GE personnel, that the Bernoulli pressure differential (vortex loading) distributions from the CFD analysis were applied statically to the dryer finite element model, accounting for the low frequency flow induced vibration (FIV) loadings. It appears that calculated stresses in the dryer hood from the ANSYS finite element analysis for all loading cases except the low frequency FIV load sets are small and insignificant. The inspectors found that the structural stress can be significant with the application of Bernoulli pressure distributions from the CFD analysis. The CFD analysis was used to establish the flow patterns around the dryer hood, and to define the pressure distributions on the hood structure due to the flow induced loads.

The CFD analysis model included half of the dryer structure due to the symmetry of the dryer assembly. Steady state incompressible flow was assumed. The inspectors found that this was a reasonable approach for establishing the flow patterns and velocity field in the dryer inlet plenum, and the Bernoulli pressure differential across the vertical and horizontal hood plates. The CFD analysis was performed using the computer code CFX-5.5.1 for both the original dryer configuration and for the modified dryer configuration. The CFD analysis results indicated that modifications to the QCNPS, Unit 2 dryer, including the addition of a vortex breaker along the top section of the hood and flow straightening gussets on the lower hood and dryer cover plates would have a positive effect on the flow field. With the vortex breaker installed over the horizontal top corner of the outer hood, the flow turbulence over the top section of the hood was mitigated. With the addition of the flow straightening gussets, the high vortex regions that existed at the dryer lower hood near the entrance to the steam exit nozzles was eliminated. The inspectors noted that with these modifications, the average pressure differential across the vertical hood plates was reduced by 22 percent.

The inspectors reviewed the finite element model (FEM) for the original dryer configuration, and the modified configuration including the hood repairs. The ANSYS computer code was used for the structural analysis, utilizing finite shell elements to represent the structural members of the dryer. The model included the dryer support ring with the cross-beams, base plate, drain troughs, dryer hoods, and the steam dam above the dryer with its support gussets. The dryer skirt was not modeled with shell elements, but was incorporated by an increase in density of the support ring. The inspectors found this to be acceptable because dead weight and dynamic interaction were accounted for with the added masses.

The inspectors found that the finite element model for the modified configuration included: (1) replacement of the damaged portions of the top and front plates of the hood with 1" thick plates, and (2) addition of three gusset plates between the cover plate and the bottom of the vertical hood plates. The inspectors noted that the stress concentration at the local discontinuity between the 1" thick replacement plates and the original hood plates was accounted for by application of a stress intensification factor of four to the ANSYS stress results. The inspectors also noted that the model which included repair modifications was constructed conservatively without taking credit for the addition of the vortex breaker welded along the top of the vertical hood plate, and the stiffener plates added at the vertical hood welds and at the top hood plate side welds. These additional members would tend to stiffen and further strengthen the modified dryer structure.

The ANSYS structural analyses included the frequency analysis of the original and the modified dryer models, the flat pressure spectrum for the low frequency FIV loading, and the high frequency acoustic loading. The inspectors found that the fundamental frequency of the vertical hood plate was increased from 24 Hz for the original model to 67 Hz for the modified model. The inspectors also found that the structural response of the modified hood to the higher frequency range acoustic loading was small and negligible. As a result, the maximum stress at the ½" thick hood plate due to the FIV loading was reduced from about 16,700 psi for the original dryer model to 1,150 psi for the modified dryer model. With the application of a dynamic load factor of 2, included in the GE evaluation to account for the dynamic nature of the pressure loadings, the maximum stress becomes 33,400 psi for the unmodified dryer model. This appeared to be consistent with the GE estimated failure stress based on a reverse engineering fatigue analysis. With application of a dynamic load factor of 2 and a stress concentration factor of 4, the stress for the modified dryer model may increase to 9,200 psi, which is below the fatigue endurance limit of the hood material. Potential fatigue failure can be prevented for the structural components with a maximum stress level below this limit.

The inspectors concluded that the modified dryer, including the 1" thick replacement plates and the flow straightening gussets will reduce stresses to an acceptable level. In addition, the inspectors noted that there were conservatisms inherent in the GE evaluation of the modified dryer. These conservatisms included applying the pressure differential distribution based on the CFD analysis of the original unmodified dryer configuration to the modified dryer model. The application of CFD pressure distribution results using the modified dryer configuration for the CFD analysis would further reduce the stress results in the modified hood structure by about 30 percent. Also, the modified model did not take credit for the addition of the vortex breaker welded along the top of the vertical hood plate, and the stiffener plates added at the vertical hood welds and at the top hood plate side welds.

.6 Review of Dryer Repairs

a. Inspection Scope

The inspectors reviewed documentation of the repaired areas of the steam dryer hood including GE Nuclear Energy (GENE) Field Deviation Disposition Requests, GENE design drawings for the dryer modifications, repair welding and inspection procedures, GE and Stearns-Roger assembly drawings of the dryer, and stress results from the ANSYS computer code finite element analysis of the modified dryer structure. The inspectors also met with Exelon and GE personnel to facilitate understanding of the details of the physical repairs and their analytical basis, and to discuss data and technical results included in the audio-visual presentation documents prepared by the licensee.

b. Findings

The inspectors found that the repairs to the upper dryer hood appear to be structurally adequate to preclude reoccurrence of fatigue-type cracking in the modified hood structure at least for the remainder of the current fuel cycle.

The damaged sections of the original ½" thick type 304 stainless steel hood plates were removed, including the internal gusset stiffeners from the failed diagonal braces, and were replaced by 1" thick type 304L stainless steel plates. The internal diagonal braces at each of the outer hood structures were not replaced, because stress results verified that these braces are not required for structural integrity of the modified hoods. Gusset plates (½" thickness) were welded to the lower hoods and to the dryer cover plates to stiffen the lower hoods, and to alleviate the formation of high velocity fluid vortices due to bi-stable flow into the main steam outlet nozzles. A vortex breaker was also welded over the top horizontal corner of the upper hood to further reduce vortex formation as steam flowed down over the top and sides of the outer hoods and into the steam line nozzles. The vortex breaker consists of a five inch diameter, schedule 120 pipe section cut in half longitudinally, and welded over the horizontal corner of the replacement 1" thick hood plates. Although this device will further stiffen the repaired areas of the hood, it was not credited as a structural member in the stress analysis, because its primary purpose is to reduce fluid vortex formation which results in a reduction of the applied pressure differential loading across the dryer hood plates. The tie bars (horizontal members stabilizing the six internal dryer banks) which failed were replaced with 1" x 3" solid bars, increasing the member cross-section and strength of the original angle section tie bars which failed.

Additional stiffeners were welded to the upper hood as a precautionary measure, even though no evidence of structural failure was present in these areas. This additional structure consists of stiffener plates welded over the vertical seam welds of the outer hoods, and angle braces welded over the top hood plate side welds.

The inspectors verified the analytical basis for the integrity of the repairs. The analytical procedure consisted of calculation of an enveloping pressure differential accounting for the flow-induced loads on the inside and the outside of the hood structure. The calculated pressure loading was applied statically on the inside surface (higher pressure side) of the hood, and a dynamic load factor was applied to account for the dynamic nature of the fluid loading. The structural discontinuities created by welding the 1" thick repair plates to the original ½" plates of the dryer hood were accounted for in the stress analysis by application of a stress intensification factor of four. The resulting stresses in both the repair plates and in the original hood plates were acceptable when compared to the allowable fatigue stress criteria of the ASME Boiler & Pressure Vessel Code, Section III, Appendix I.

Due to radiological considerations, all welding and inspection was performed with the dryer assembly submerged in the water filled Dryer/Separator Equipment Pool. Welding was performed by the Underwater Construction Corp. The inspectors reviewed the GE Process Specification No. P50YP244, Revision 10, “Structural Arc Welds in All-Water Environment” and found it acceptable for this application. Certifications for Underwater Construction Corp. NDE personnel were reviewed and found to be in accordance with ANSI N45.2.6, 1978. Underwater Construction Corp. welding procedure specification No. N-516G-3-1-8, Revision 0 and the associated procedure qualification record were also reviewed and found to be in accordance with the ASME Code Section IX and Code Case N-516, “Underwater Welding”. The original GE specification for the dryer assembly, “Standard Requirements for Steam Dryer” dated November 30, 1966, required that welds be inspected with liquid penetrant. Since the dryer was submerged for the repair welding, Code Case N-516-2 was invoked due to the impracticality of liquid penetrant inspection. This Code Case was approved for use at QCNPS and included in the current Inservice Inspection Plan. The Code Case provides for the use of visual inspection techniques when a surface examination such as liquid penetrant is impractical. The inspectors reviewed selected portions of the repair weld inspections video and found the weld quality acceptable.

.7 Evaluation of Root Cause Efforts

a. Inspection Scope

The inspectors reviewed the audio-visual presentation data and accompanying photographs, and the remote camera videotapes of the damaged areas of the dryer hoods to gain insight into the potential cause of the dryer failures. The inspectors also met with GE personnel to discuss the results of stress analyses performed on the original unmodified structure. These analyses were performed by GE to develop various options for design of the repairs, and provided some additional evidence to support the expected root cause of the QCNPS, Unit 2 hood failures.

The inspectors met with GE personnel to discuss the results of the steam dryer flow test program to understand the application of those results to the QCNPS, Unit 2 dryer geometry, and the potential for application of those results to other BWR steam dryers.

b. Findings

The inspectors found that the root cause determination for the steam dryer hood failures, and assessment of the extent of condition potentially affecting other parts of the dryer assembly, were not complete at the time of the special inspection. Further work is ongoing, including metallurgical examination of the failed material samples removed from the dryer hood to further identify the failure mechanism. Further analytical work is also proceeding, including flow analysis and evaluation of flow testing options to provide more complete understanding of the complexities of the flow-induced vibratory loadings affecting the steam dryer under EPU conditions.

The inspectors concluded that, based on information available at the time of the special inspection, including the results of stress analyses, CFD analyses, and remote camera visual inspection of failed surfaces, the root cause of the upper hood cracks appears to be high cycle fatigue due to flow-induced vibration occurring at a frequency range between 0 - 50 Hz. This forcing function frequency range envelopes the natural frequency of the original unmodified dryer hood structure, which could have resulted in a resonant condition producing large vibration amplitudes in the upper hood. The modifications to the upper hood structure increased the natural frequency of the hood plates to 67 Hz, which avoids the driving flow-induced frequencies in the 0 - 50 Hz range, and the higher acoustic frequencies in the 180 Hz region which were identified as the cause of the earlier dryer cover plate failures. The licensee's completion of the ongoing work required for the final root cause determination is necessary in order to confirm these observations.

The inspectors found that the licensee's efforts in determining why these failures have thus far occurred only at QCNPS, Unit 2 were inconclusive at the time of the special inspection. The licensee has identified certain unique aspects of the QCNPS, Unit 2 design that may or may not contribute to the basis for explaining why these dryer failures have occurred only at this particular reactor. QCNPS, Unit 2 is the only plant of this type with power operated relief valves (PORV) on the main steam lines. However, GE conducted a CFD analysis of the loads applied to the dryer hood from a PORV transient. Application of these loads to the dryer finite element model resulted in relatively low stress levels in the dryer hood. Scale model flow testing conducted by GE demonstrated that relatively small variations in steam line length, including inlet piping to safety and relief valves, could change the magnitude of pressure loads on the dryer assembly. However, the flow test results suggested that flow-induced loadings on the dryer associated with the attached main steam lines occurred as acoustic, high frequency (~180 Hz) waves which are significantly removed from the natural frequencies of the steam dryer hood before and after modification. Therefore, the resonant condition with high frequency loading causing fatigue failure in the dryer hoods would not be expected. Consequently, it remains unclear whether these aspects of the QCNPS, Unit 2 design provided any unique contributions to the recent failures of the steam dryer hood structure.

The inspectors discussed the generic implications of the dryer failures with the licensee, including the potential for further failures in other parts of the QCNPS, Unit 2 dryer, as well as the potential for dryer failures in other BWR/3 reactor designs that are licensed to operate at similar EPU power levels, e.g., QCNPS, Unit 1 and Dresden, Units 2 and 3. Without the final root cause determination, which was estimated to require another four weeks to complete, the licensee, at the time of the special inspection, was unable to discuss any further evidence to provide an increased level of confidence that additional dryer failures in other parts of the structure would not occur.

4OA6 Meetings

Exit Meeting

The inspectors presented the inspection results to Mr. T. Tulon and other members of licensee management at the conclusion of the inspection on June 26, 2003. The inspectors asked the licensee whether any materials examined during the inspection should be considered proprietary. Some analyses performed by GE were considered proprietary. Those portions of the analytical work by GE considered proprietary were reviewed by the NRC inspectors, however, they are not discussed in detail in this report.

KEY POINTS OF CONTACT

Licensee/GE Nuclear Energy
T. Tulon, Site Vice President
T. Wojcik, Engineering Programs Manager
R. Phares, Engineering Programs
W. Beck, Regulatory Assurance Manager
G. DeBoo, Senior Staff Engineer
K. Moser, Asset Management Engineering
J. Klapproth, GE Engineering Manager
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M. Patel, GE Engineering
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Nuclear Regulatory Commission:
S. Reynolds, Deputy Director, Division of Reactor Projects
M. Ring, Chief, Reactor Projects Branch 1

LIST OF ACRONYMS

ADS	Automatic Depressurization System
MW_e	Megawatts Electric
MW_{th}	Megawatts Thermal
EPU	Extended Power Uprate
QCNPS	Quad Cities Nuclear Power Station
PORV	Power Operated Relief Valve
FIV	Flow Induced Vibration
FEM	Finite Element Model
NDE	Nondestructive Examination

LIST OF DOCUMENTS REVIEWED

LER 50-265/02-03; Reactor Shutdown due to Failure of Reactor Steam Dryer from Flow-Induced Vibrations as a Result of Extended Power Uprate

Quad Cities Unit 2 Operating License

Quad Cities Unit 2 Visual Inspection History; dated June 24, 2003

GE-RPT-Q2M20-02-JLM6J; Final Report and Supporting Documents for Quad Cities Unit 2 Steam Dryer Repair; dated July 22, 2002

Identification Notification Report-Q2M20-02-02; Steam Dryer Outer Bank Hood at 90 Degrees; dated July 13, 2002

Identification Notification Report-Q2M20-02-03; Steam Dryer Bank Vertical Welds; dated July 13, 2002

Quad Cities Unit 2 Moisture Carryover Time Line; dated June 23, 2003

Quad Cities Unit 1 Moisture Carryover Time Line; dated June 23, 2003

Quad Cities Unit 2 Moisture Carryover Sampling Schedule from March 6, 2002 - June 10, 2003

Graphical Representation of Quad Cities Unit 2 Carryover History 1992 - Present

Operability Determination 158145-08; Degraded Unit 2 Steam Dryer; Revisions 0 and 1

Operability Determination 111976-09; Degraded Unit 2 Steam Dryer; Revisions 0 through 5.

QCCP 0800-13; Reactor Water Carryover and Powder Demineralizer Radioactive Removal Efficiency; Revision 3

Condition Report 157494; Elevated Moisture Carryover Indicated on Unit 2; dated June 9, 2003

Condition Report 158145; Unit 2 Moisture Carryover Increase; dated May 9, 2003

Condition Report 160858; Unit 2 Moisture Carryover is Elevated; dated May 28, 2003

Condition Report 162964; Unit 2 Dryer Failure; dated June 12, 2003

Quad Cities General Abnormal Procedure (QGA) 200; Primary Containment Control; Revision 8

GE Nuclear Energy Service information Letter (SIL) No. 644, “BWR/3 Steam Dryer Failure,” 08/21/03.

GE Report GE-NE-T2300700-17-17-01, “Lost Parts Analysis for Potential Steam Dryer Lost Parts in Quad Cities Generating Station Unit 2,” 06/18/02 (Proprietary).

Underwater Construction Corp. Welding Procedure Specification N-516G-3, Rev. 4, 02/05/03.

INPO SER 5-02, “Lessons Learned from Power Uprates,” 08/21/02 (Proprietary)

GE Drawing series 728E947, Steam Dryer, 12/02/66

Stearns-Roger Assembly Drawings, L-21571, Steam Dryer, GE, Dresden; L-21573 through L-21581, Steam Dryer, Dresden - Quad Cities, 1968-1969

GE Drawing 104R921, Sheets 2 and 3, Reactor Assembly, Quad Cities 1&2, 05/29/68

GE Field Deviation Disposition Request No. EE2-0525, Description of Quad Cities Steam Dryer Installation of (Vortex) Mitigation Braces,” 06/19/03

GE Field Deviation Disposition Request No. EE2-0532, Description of Removal of Cracked Sections of Dryer Hood and Replacement of Removed Sections, 06/18/03

Commonwealth Edison Drawing No. M-101, Main Steam Piping Plans and Sections, Rev. M, 03/11/96

GE Drawing 105E3655, Steam Dryer (Modifications), Rev. 1, 06/16/03 (Proprietary)

GE Report, GENE-0000-0018-0985-01, “Stress Analyses for The Quad Cities Unit 2, Stream Dryer Repair.” (Proprietary) Revision 1, June 2003.

ANSYS Computer Code Version 6.1

GE Procedure, GENE-0000-012-0018-1651, “Root Cause Evaluation Process,” (Proprietary) June 2003.

GE Report, GENE-0000-012-0017-6545, “Reverse Stress Analyses for The Quad Cities Unit 2, Stream Dryer Repair.” (to be published)

GE Design Specification, 26A5450, Revision 1, “Hold Down Replacement, Steam Dryer,” (Proprietary) 7/18/00.

GE Report, GENE-0000-0017-7600-01, “Quad Cities Unit 2 Dryer Repair, CFD.” Class 3 (Proprietary), June 2003.

GE Document, DRF-0000-0009-4020, “Dryer Test Design Review.” (Proprietary)

GE Document, GENE-189-11-0292, “Steam Dryer Vibration Measurement Program,” Class III (Proprietary), March 1992.

GE Report, MDE 199-0985, DRF-B11-00314, “Susquahanna-1 Steam Dryer Vibration, Steady State and Transient Response,” (Proprietary) October 1985.

GE Report, NEDE-0000-0018-1636, “Steam Dryer Outer Hood Time History Analyses,“ (to be published)