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Executive Summary

Over the past 3 plus years, Duke Energy Florida LLC (Duke), at times working independently and at times together with Mitsubishi Hitachi Power Systems (MHPS), undertook a root cause analysis (RCA) of the cause(s) for the Unit 4S L-0 blade cracks and failures that occurred during normal station operations at Bartow Station. The intervals between failures had become shorter after each failure despite MHPS's attempts to improve the blades' performance and the station's adherence to the revised OEM operating instructions received after each successive failure.

Only after the telemetry test was completed and after the onset of Period 3, in approximately March 2015, (as a result of the telemetry test) did MHPS create an "avoidance zone" in which the station was not to operate except as needed to ramp up or down. Bartow operated in the avoidance zone only 1.15 hours in Period 4 and 0 hours in Period 5, but suffered two (2) further failures in successively shorter periods. Thus, after the fifth failure, Duke concluded that operation in MHPS' designated avoidance zone did not explain the failures and looked at whether other factors potentially were related or contributed to the failures.

Duke considered both operational and design aspects. With respect to operational factors, the Duke team used the Plant Information ("PI") data historian and operational data from each period and retroactively calculated¹ whether those factors had any correlation to the failures. Potential factors in the operational category included:

- Operations in MHPS Avoidance Zone -- Low Pressure (LP) Turbine "Excessive" Steam Flow
- Bartow Blending Operations -- Potential Thermal Distress (Rate of Change in Super Heat Over Time, dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)

Duke Engineering concluded that there was no correlation between any one of the above-listed factors and the five (5) failure periods. Notably, Duke was only able to study each factor independently based on available data. In the absence of (1) blade telemetry, (2) duplication of the factors in various combinations, and (3) operation in varying but normal conditions, it is not possible to study how each factor relates to and interacts with any other factor, if at all.

Duke also studied design factors unique to MHPS 40" steel blades. This aspect of the RCA was largely deductive because MHPS controls design data, although MHPS did provide FEA stress and frequency analyses, material properties, and some dimensional information. The following factors were included in this portion of the study:

¹ Because MHPS's operational constraint called the Avoidance Zone was not provided by MHPS until after the onset of Period 3, one could only look at hours in that zone after-the-fact for Periods 1 and 2.

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- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

With regard to the "Hard-Facing on Mid-Span Snubbers" factor, Duke was able to conclude and MHPS concurred, that this factor played a part in the blade failure in Periods 3 and 4. With respect to the Zone Analysis and Blade Fitment factor, although MHPS made no concession, it is currently re-engineering its 40" blades and making changes to the blades' geometry as discussed by MHPS Engineering in a 22 September 2017 presentation made to Duke.

Based on its observations and study, Duke has been and remains of the opinion that the root cause of the failures in the ST L-0 40" blades is the blade design/lack of blade design margin. That is to say, under expected operating conditions at Bartow's 4x1 Combined Cycle (CC) Unit, the MHPS blades are substantially more fragile than similar 40" blades both in Duke's CC fleet and elsewhere in the industry.²

Duke's conclusion is based on its study of the events and information that includes data supplied by MHPS, PI data from Bartow, information from similar units in Duke's fleet, and industry experience with the 40" blades. MHPS did not provide proprietary information concerning engineering and testing of the 40" blades but did provide engineering assistance and strain gauge data from a brief period of MHPS-led telemetry testing during December 2014. Duke provided all operational information requested by MHPS and met with MHPS multiple times to discuss both MHPS' findings and Duke's independent research and findings. This RCA report is Duke's product and presents its view of the root cause based on all inputs received.

For Bartow, the long-term solution is to replace the L-0 blades with blades of a different design and/or to retrofit the LP steam path and/or continue operation with pressure plate.

With either a redesign of the MHPS 40" blades or replacement with blades of a different make or an LP steam path retrofit, telemetry instrumentation and blade vibration monitoring are necessary to ensure that all potential upset conditions are resolved.

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Historical Overview

Bartow is a 4x1 CC Station with a steam turbine (ST) manufactured by MHPS. The ST was purchased from Tenaska Power Equipment, LLC (Tenaska) which intended to use it for a 3x1 CC with a gross output of 420MW. The ST was never delivered to Tenaska and remained with MHPS in a warehouse in Japan until Duke purchased the unit in 2006.

² The most commonly reported issue with the 40" L-0 blade design elsewhere is water erosion, which both Duke and MHPS agree is not a contributing factor to the Bartow failures.

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Before the ST was purchased by Duke, Duke contracted with MHPS to evaluate the ST design conditions and to update heat balances for a 4x1 CC configuration. MHPS updated the heat balances for use in a 4x1 CC configuration. CC units blend steam from the combustion turbines (CT) as they start-up and/or shut-down with steam to the ST. These blending events, which are a common occurrence for CC units, result in brief periods of higher steam temperatures and flows into the condenser near the ST L-0 blades.

Since commissioning of the Bartow ST in 2009, there have been five (5) events involving L-0 blade failures and/or replacements as described, below.

Each 40" MHPS steel blade is twisted with a "root end" that connects it to the hub, a snubber at the mid-point or mid-span, and a shroud with airfoil tips at the top. While the ST spins up to its operating speed of 3600rpm, each blade elongates and starts to untwist. The snubbers and airfoil tips are designed to contact each other and create a stabilizing central and outer ring. If a snubber or airfoil tip fails, the blades can vibrate excessively and can cause sudden catastrophic failure. Although none of the five (5) Periods at Bartow involved a complete blade loss or catastrophic failure, two (2) involved upsets and each event affected mid-span snubbers, shroud Z-Locks, and airfoil tips.

The five (5) Periods are summarized in Table A. Each Period's start date is when the ST was put into service and each end date reflects either when the ST was taken off-line or suffered an unplanned outage. The blades for each period are described by "Type." The ST was sold and during Period 1 was operated with Type 1 blades, which at MHPS' recommendation and urging were replaced – turbine end (TE) blades only – with a re-engineered Type 1 blade at the start of Period 2. Period 2 ended with a planned shut-down, during which the TE and generator end (GE) blades were replaced with an OEM-improved design (Type 3) even though the in-service Type 1 L-0 blade condition was such that they could have run longer. The Type 3(v1) blades had hard-facing on the mid-span snubber contact surfaces and MHPS ran its brief period of telemetry testing. Damage found at the end of Period 3 resulted in a forced outage and the installation of new Type 3(v2) blades with hard-facing on the mid-span snubber, as well as hard-facing now added to the Z-Lock contact surfaces. When these Type 3(v2) blades failed at the end of Period 4, they were replaced with the original Type 1 blades for Period 5. When these Type 1 blades failed at the end of Period 5, the L-0 blades were replaced with a pressure plate.

MHPS provided OEM operating parameters in each Period as reflected in Table A under the heading "MHPS IP Exhaust Pressure Operating Limits." For Period 1, these limits were the design limits that accompanied the ST at purchase. After the damage was discovered at the end of Period 1, MHPS imposed a lower IP exhaust pressure limit. In Period 3, when the Type 3 blades were installed, MHPS raised the limit, in accordance with the original proposal by MHPS to supply blades for Period 3 that would allow operation up to 450 MW but also stay within the limits established as a result of the telemetry test. After the telemetry test, MHPS sent out a chart it called the "Avoidance Zone" and suggested that blade damage would be avoided if Duke operated as few hours as possible in the zone. The practical result of the avoidance zone limits meant that the Bartow ST unit could not achieve 450

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MW as the IP exhaust pressure was, and to this day still is, limited when condenser pressure is in a range the unit normally must run in. In Period 4, with the discovery of additional damage, MHPS lowered its IP exhaust pressure limit and did so again in Period 5.

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Table A: Bartow L-O Events Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	June 2009 to March 2012	April 2012 to August 2014	December 2014 to April 2016	May 2016 to Oct 2016	December 2016 to February 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-O Blade Configuration	Type 1	Type 1 (re-engineered)	Type 3 (v1)	Type 3 (v2)	Type 1
MHPS Expected ST Output	420 MW (Nameplate)	420 MW	450 MW ³	450 MW ³	390 MW
MHPS IP Exhaust Pressure Operating Limits	Machine controlled to HP, IP and Condenser design limits	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111.5 psig Limit on IP Exhaust
Retroactive Calculation of Avoidance Zone "Exceedance" based on the MHPS Period 3 Avoidance Zone chart ⁴	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,284 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period	<p>Planned outage for valve work, as well as annual L-O inspections.</p> <p>At the start of this period, MHPS approved 4x1 (unfired) operations at 392 MW output, as well as 3x1 (duct fired) operation at 420 MW, supported by MHPS-provided heat balance documentation</p> <p>During a plant shut down a visual inspection of the ST L-O blades revealed damage to the turbine end blade snubbers.</p>	<p>Planned outage for upgrade to "heavy duty" blades, based on MHPS representation that it had improved design</p> <p>Some blade damage (e.g. chipping at contact corners) was observed from removed service blades</p>	<p>Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.</p> <p>During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits – unit ran in zone for <20 hrs.</p> <p>Planned outage for valve work, as well as an annual L-O inspection</p> <p>No blade cracking observed after testing (when the test instrumentation removed).</p> <p>Stallike hard-facing added to snubbers only.</p>	<p>Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.</p> <p>Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil.</p> <p>Stallike hard-facing added to the blade Z-Lock.</p>	<p>Jan 2017 "loss of mass" event – blade fragment projectile traveled through the IP turbine rupture disk diaphragm.</p> <p>Dental mold impression of failure surfaces indicate ~10⁴7 strutations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber)</p> <p>L-O blades removed and pressure plate installed; pressure plate restricted ST output to between 360-380 MW. MHPS maintains operational restrictions on ST.</p>
Information Shared with MHPS	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.

³ Outside of operation in the MHPS Avoidance Zone

⁴ For purposes of comparison, the Duke RCA team looked at hours in the Avoidance Zone even for periods in which that concept had not been introduced.

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Operational Factors Potentially Impacting MHPS Blades**Low Pressure (LP) Turbine Excessive Steam Flow – “Running in the Avoidance Zone”**

After the Period 3 outage was concluded and the ST was back in service, MHPS offered a view that high back-end loading on the LP turbine last stage blades must have been a significant contributing factor to the past L-0 blade damage/failures. Back-end loading is created by steam flow and operating pressure through a turbine section. Based on hindsight, MHPS Engineering claimed that at the time of the first failure (Period 1), Bartow Unit 4S exceeded the back-end loading limitation of 15,000 lb/hr-ft² by many hours and that the MHPS 40” L-0 fleet average for back-end loading was closer to 12,000 lb/hr-ft². Although MHPS had not previously imposed a back-end loading limitation, it then created what it called the “Avoidance Zone” and suggested longer run times in the avoidance zone were the root cause of the first three failures.⁵

Then and now, Duke Engineering does not agree that back-end loading above 15,000 lb/hr-ft² has been the failure-driving mechanism for the documented L-0 events. As Table A illustrates, Periods 2, 4 and 5 saw operating hours in the MHPS defined “Avoidance Zone” of only 1 hour, 1.15 hours and 0 hours, respectively, and still Bartow suffered damaged blades. Period 3 had only 240 hours in the avoidance zone, less than 2% of its total operating hours. Furthermore, by a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the “avoidance zone” – 2,466 out of 21,734 total hours – but despite the greatest number of hours, blade damage in this Period was limited to five (5) broken mid-span snubbers on the TE of the machine and a lesser degree of fretting on the shroud Z-Lock contact surfaces for both TE and generator end (GE) of the machine than seen in other Periods. The next highest period in the avoidance zone, Period 3, with 240 hours (out of 10,286 total hours – (11 hours of which were during approved instrumented blade telemetry tests performed by MHPS in December 2014), showed significantly greater amounts of blade damage and fretting to the Z-Lock contact surfaces on both ends of the machine than Period 1.

While the amount of Z-Lock wear cannot be quantified for Periods 1 and 3, photographs show the difference (See Figure 1 below).

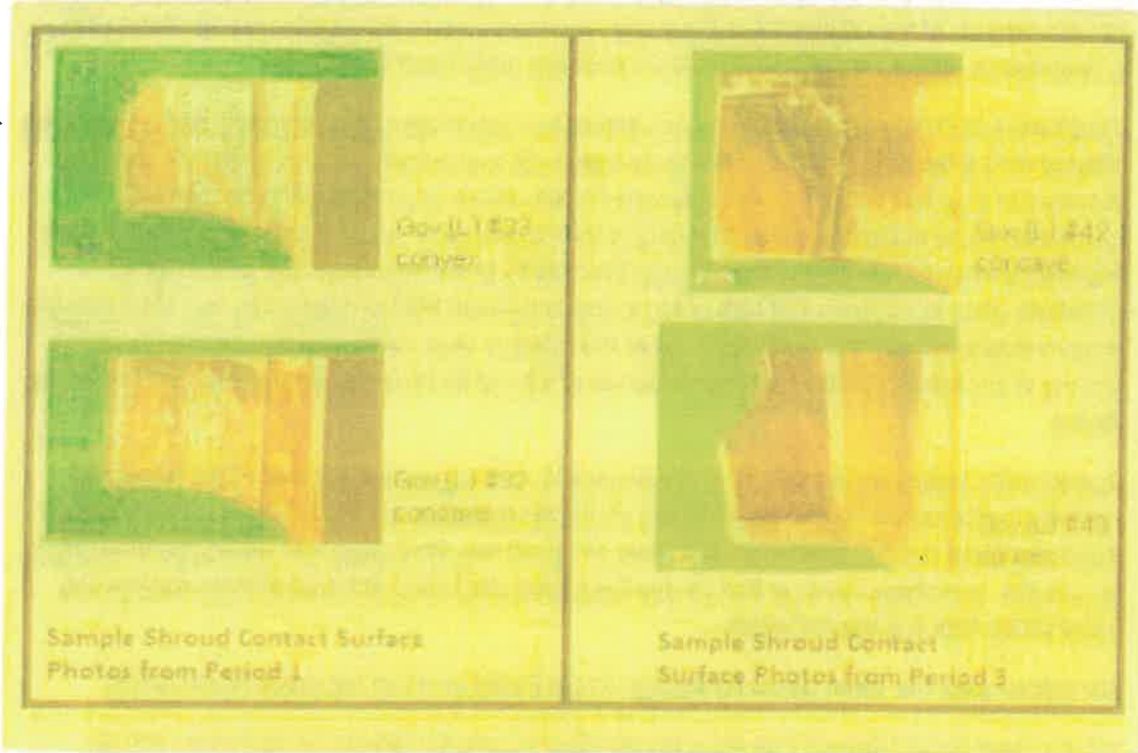
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⁵ MHPS Engineering extrapolated the December 2014 data to isolate operation in the Avoidance Zone as the root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil as seen during Periods 1-5. Duke Engineering does not agree that this data can be extrapolated over all five Periods, in part, because the data does not include normal operating conditions at Bartow and in part, because the information does not explain what occurred in each Period. Without telemetry over a sufficiently long period, under a sufficiently normal set of operating conditions after new blades and/or other equipment is installed, the December 2014 data yields no reliable RCA conclusions.

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Figure 1 –Photos of Shroud Contact Surface Wear for Periods 1 and 3



Based on comparative run times and damage, it is difficult to conclude that the L-0 blade damage in each Period or any particular Period is due to unit operation in the avoidance zone.⁶

Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust – “Blending Operations”

After the Period 5 failure, which occurred with zero hours in the avoidance zone and with no other explanation offered by MHPS, the Duke RCA team began to consider whether other operational aspects might impact exhaust conditions of the LP. The Duke team looked for other mechanisms that might introduce forces great enough to initiate cracks in snubbers including Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF). The two (2) operational conditions that might conceivably produce forces great enough to initiate snubber cracks are blending and the use of hood sprays (especially with low out-of-spec inlet pressure). Blending is discussed first.

⁶ Even though the L-0 blades are no longer in the ST and a pressure plate has been installed, MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current IP Turbine exhaust pressure operating limits because of “potential impacts to upstream blading” – i.e. the L-1 blade sets. This suggest that MHPS is unsure what effect if any is created by its “avoidance zone” and more importantly points to a design flaw that may affect more than the L-0 blades.

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Since the design of the condenser includes spargers (or "dump tubes") for the hot reheat (HRH) and LP bypass steam flows from each of the four (4) CTs, and since thermocouples positioned at the LP exhaust just downstream of the L-0 blades (i.e. hood spray thermocouples) have experienced significant changes in temperature during a blend operation, Duke reviewed these blend operations.

Using Excel and PI Datalink, Duke Engineering determined which operational blending events might have affected the L-0 blades in order to isolate those higher risk events from the large quantity of blending operation of data for Periods 1-5. Duke identified blends with a slope change greater than 20° superheat/minute at the hood spray thermocouples and with an ST output greater than 50 MW. Duke Engineering selected the 20° F change in superheat and 50 MW minimum output as proxies for conditions when blend steam had high or low enthalpy (LCF and HCF) as reflected by high thermocouple temperature/superheat rate of change.⁷ While this measure does not necessarily indicate the overall severity of any loadings on the L-0 blades, it serves as a proxy for reviewing events which could load the blades.

Operationally, blends are not defined or constrained to strict parameters because of the number of variables that can affect blends. High and low enthalpies therefore, are not functions that are typically monitored by an alarm or otherwise. This study of blends was done solely with the benefit of hindsight for this RCA. In studying blends at Bartow, the Duke team also looked at blends at other stations and found similar high and low enthalpies.

The following are the blend counts for Bartow in each Period based on the above-listed criteria:

Table B – Number of "Counts" that Meet the Blending Criteria for Periods 1-5 on Bartow Unit 4S.

	Number of Operating Hours in Each Period	Number of Blends (or "Counts") Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

*Includes 6 blends during strain gauge testing in December 2014

Using the same criteria as used for Bartow, blending operations at the HF Lee CC plant and for Hines Energy Power Block 2, which have 40" and 42" L-0 blades, respectively (but from different OFMs than MHPS), were used as a basis of comparison to Bartow – see Table C.

Table C – Number of "Counts" that Meet the Blending Criteria on the HF Lee CC ST

⁷ Although Duke could have used smaller temperature changes, selecting small changes (e.g. a three- or five- degree difference) would yield too many results, most of which could not cause a LCF or HCF effect. Likewise, at too-high a temperature delta, too many data points may have been eliminated.

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Duke Station	Date Range	Number of Operating Hours	Number of Blends (or "Counts") Meeting Criteria
HF Lee CC ST	01/01/2014 to 01/01/2016	15,045	22
Hines PB2 ST	09/01/2015 to 09/01/2017	16,123	44

Given the comparison with Lee and Hines CC STs and the variability in blending events in the Bartow Periods, Duke was unable to draw any correlation between blending and the impacts on the MHPS blades. Bartow, Hines and Lee are similar in their blending rates and blending counts and yet, Lee's and Hines' blades have never been impacted like what has been seen at Bartow. This reinforces the Duke team's conclusion that the Bartow failures are attributable to the design or slim design margins in the MHPS 40" blades.

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke team also studied whether hood spray operations were a possible cause of high and low energy forces on the L-O blades because of the proximity of the sprays to the L-O blades. The hood spray nozzles rely on pressure drop across the nozzle to create a vortex inside the nozzle that causes atomization of the water through centripetal force. Reduced pressure drop corresponds with a reduction in atomization and lower hood spray atomization may create dynamic pressures affecting the L-O blades, as large water droplets evaporate/flash-off in the exhaust stream creating pressure pulses.

The hood spray operation is programmed into the Ovation DCS control system and is automated with no operator interaction. The condensate pump output acts as a source of water for the spray. A control valve reduces the roughly 500 psig condensate pressure to the spray design pressure of 50 psig. A review of the OEM-provided instructions directs use of hood sprays during the following two conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160° F

Although not clear why, the Bartow hood spray data shows that the hood spray had been programmed during unit construction to operate any time blending takes place – similar to curtain sprays. Duke is not able to determine who programmed the hood spray in this way; MHPS would have had input in the control system but the architect/engineer typically designs the plant-wide control system.

In any case, because of the manner it was programmed, the hood spray operations occurred at greater rates than would have normally occurred. Two questions are raised in hood spray operations: (1) are the temperatures at the hood spray thermocouples normal or excessive and (2) is the hood spray pressure normal?

Hood spray thermocouple data shows the hood sprays rarely reached 160° F during normal operation and never exceeded 165° F. Higher temperatures are sometimes seen after a shutdown or unit trip as

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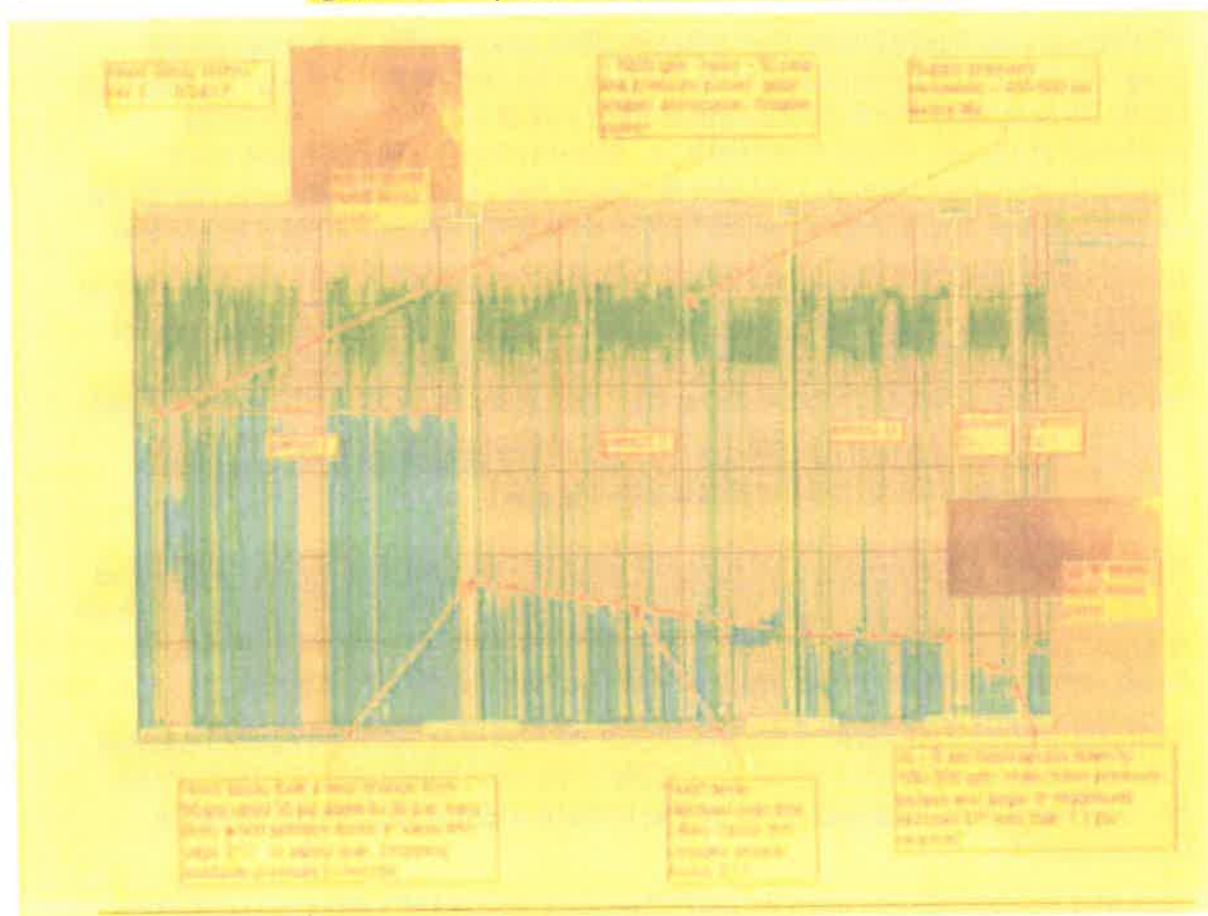
exhaust pressure increases, most likely due to the hot LP casings and some windage. During shutdowns and/or unit trips, there were no temperature readings above 201° F (one very brief reading of 1040° F was the result of an instrumentation issue).

Having eliminated excessive LP exhaust temperature as a concern, the team looked at hood spray pressure and found it had steadily decreased over successive Periods likely due to clogged sprays.

Figure 2 depicts the pressure decrease in the hood sprays over time. The decline in water pressure at the hood spray nozzles, likely caused by debris in the valve trim, results in reduced atomization.

At the kind of hood spray pressures shown in Figure 2, the atomization of the hood sprays would have been poor. Larger water droplets will cause pressure pulses as evaporation occurs, during times when the LP exhaust steam temperatures are elevated during blending.

Figure 2 – Hood Spray Pressure Degradation Over Periods 1-5



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Control of the hood sprays is automated within the plant-wide control system and not controlled by the operators. After a plant is commissioned, the hood sprays are not normally checked for accuracy and again, until there had been successive failures, there was no reason to focus on the hood spray system's functionality. Although the review that was conducted after the 5th failure revealed lower pressure which may have contributed to some additional wear of the blades, the Duke team does not believe this is the root cause of the failures as the design of the blades should have been robust enough to withstand some increased pressure pulses. Further, MHPS does not believe that any pressure pulses from the hood spray would have been strong enough to harm blades.

Zone Analysis – Shroud Fretting Fatigue

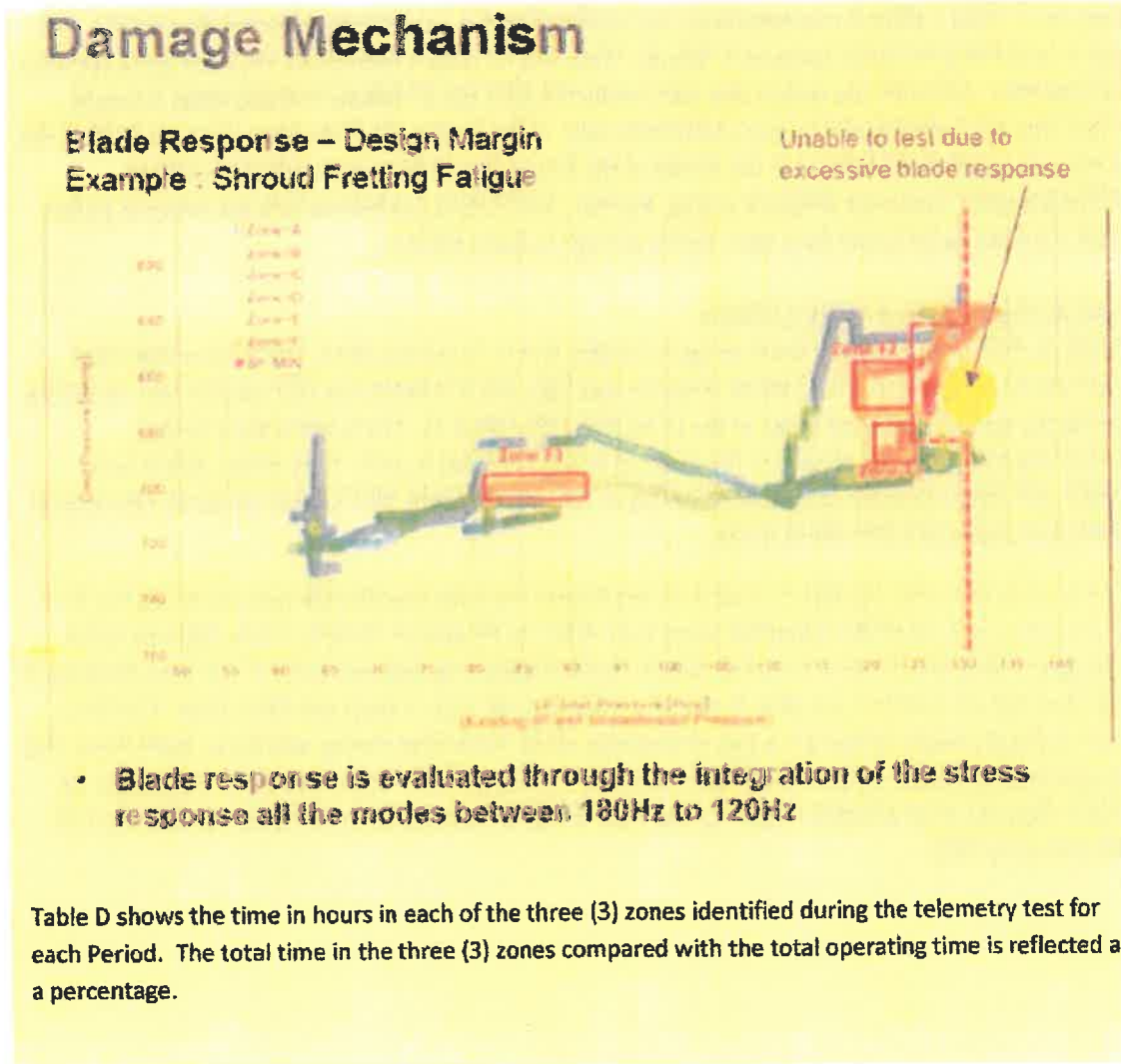
Based on data from the blade strain gauge telemetry test in December 2014, MHPS identified areas (referred to as "zones")⁸ where blade response was high, but still below the OEM design limit, occurring during the normal operation range of the LP turbine (See Figure 3). These zones were neither something Duke was told about nor the result of any operational factors. They simply reflect how MHPS' 40" blades function at certain operating conditions. Notably, MHPS never issued an operational restriction associated with these zones.

As part of its RCA after the fifth and most recent failure, the Duke Engineering team reviewed the time of operation in these MHPS-identified zones in an effort to determine whether there might be some correlation between the zone time and failure. Duke Engineering was interested in this issue because of the observed excessive Z-Lock wear in Period 5 that occurred after a short operation time. Excessive wear at these contact surfaces is a sign of excessive blade movement during operation. Since there was no operation in Period 5 above the IP turbine exhaust pressure limit "avoidance zone" designated by MHPS, the only other possible reason for the wear is higher dynamic stimulus (Zone F as identified by the telemetry test).

⁸ These zones are not MHPS operational constraints and differ from the Avoidance Zone discussed above.

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Figure 3 – Data Presented by MHPS During a Presentation Dated 15 March 2017



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Table D – Time (in Hours) in Each Zone and Compared with Operating Time

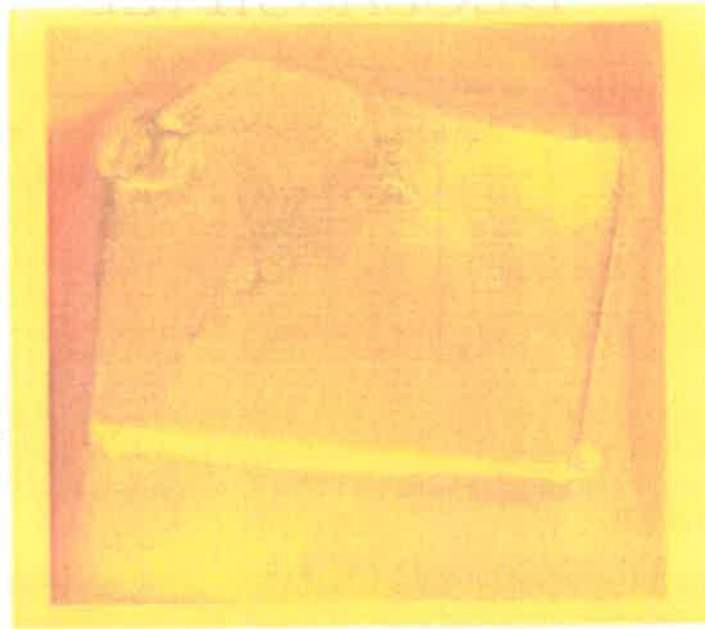
	Time in Zone				Total Turbine Operating Hours	% Time in Zone F
	F1	F2	F3	Total		
Period 1	901.2	466.2	9.7	1377.0	21734	6.3%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

Figure 4 shows the wear on one of the Period 5 Z-Locks. While varying degrees of wear are seen on the Period 5 Z-Locks, the wear is higher than what one would expect given the relatively low total turbine operating hours. Period 5's time in blend mode was consistent with those in other Periods and does not explain the amount of wear.

While the findings are not completely conclusive, there is good reason to believe that MHPS' design may be susceptible to damage when run in these zones. All Periods had hours in Zone F1 and F2. In addition, both on a percentage and absolute basis, Period 5 had a significant number of operating hours in this higher dynamic stress zone. Because each Period included run times in one or more zones and because each Period resulted in differing degrees of damage without direct correlation to the run times in those zones, it is difficult to conclude that operation within the zones is the cause of the L-0 blade failures. However, if the design margin on the blades is small, the blades may be susceptible to cracking, excessive wear, etc., when the unit either runs in or passes through these zones.

Figure 4 – Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear

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Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

High Velocity Oxygen Fuel (HVOF) hard-facing can reduce the amount of base material fretting (wear) during operations and has many applications for blading contact surfaces in the industry. HVOF hard-facing can also change the frictional forces of the contact surface by reducing the coefficient of friction. However, as frictional forces are reduced, so are the dampening forces derived from them. A reduction in dampening, in most cases, means an increase in dynamic forces and motion.

Duke Engineering considered whether dampening loss may have been a contributing factor during Periods 3 and 4, when MHPS provided HVOC hard-faced coating on certain parts of the blades. In Period 3, only the mid-span snubbers had hard-facing. As a result, the shroud Z-Lock contact surfaces had more damage relative to other Periods, likely due to a loss of dampening at the snubbers. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

In Period 4, both the mid-span snubbers and the shroud Z-Lock contact surfaces had hard-face coating. Given that both the mid-span and shroud contact surfaces were HVOF-coated, the limiting factor then became the blade airfoil high stress location in the trailing edge, which was the observed failure at the end of Period 4. In discussions with MHPS, MHPS agreed that its attempt to harden the blade contact surfaces likely contributed to the failures in Periods 3 and 4.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

To understand this issue, recall that at high speeds the Z-Lock and snubbers act as the mechanism by which the 40" blades are prevented from untwisting completely and moving loosely. Thus, the distance

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between Z-Locks and between snubbers must be precisely engineered to account for expansion and movement between the blades during operation. If the blades are too tight, (initial clearances too small) there will be too much force at the contact surface raising stresses and make breakage more likely, and if too loose (initial clearances too large), there will be too little force to provide proper dampening or allow blade vibration frequency and modes to change, potentially leading to failure.

Between Periods 3 and 4, Duke raised technical questions relative to "as left" blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. These questions were concerned with whether blade gaps at both points should be viewed together.

Because MHPS installed telemetry and conducted strain gauge testing for a short period in December 2014 at the beginning of Period 3, the Type 3(v1) L-0 blades were used to establish a baseline blade response to capture "worst case" geometry variations.

MHPS concluded that the dimensional tolerance between the Type 3(v1/v2) blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 blade (Periods 3 and 4) showed greater distortion than the Type 1 blade (Periods 1, 2 and 5).⁹ With a greater geometry variation, the Type 3 blade provided less mechanical dampening (relative to the Type 1 blade) because of the smaller contact area and misalignment.

While MHPS contends that geometry variation on the Type 3 blade is not significant enough to have negatively impacted blade stress/response, MHPS also implicitly acknowledges that blade fitment/geometry is important in its current efforts to redesign the 40" blade following the fifth failure. In fact, it is changing the geometry in response to specific Duke suggestions.

In conclusion, Duke Engineering believes that the "as-left" placement of the blades in the 3rd and 4th Periods had some impact on the failures, though again, had the blades been more robust, they may not have failed to the extent seen in those Periods. MHPS bears the responsibility for this cause as the replacement Services were entirely in its control.

CONCLUSION:

Based on its observations and study, Duke has been and remains of the opinion that the root cause of the failures in the ST L-0 40" blades is the blade design/lack of blade design margin. That is to say, under expected operating conditions at Bartow's 4x1 Combined Cycle (CC) Unit, the MHPS blades are substantially more fragile than similar 40" blades both in Duke's CC fleet and elsewhere in the industry.¹⁰

⁹ These findings are consistent with an independent analysis of the blades by Duke using third party scanning.

¹⁰ The most commonly reported issue with the 40" L-0 blade design elsewhere is water erosion, which both Duke and MHPS agree is not a contributing factor to the Bartow failures.

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Duke Energy Florida
Docket No. 20190001-EI
Witness: Swartz
Exhibit No.: JS-2

February 6, 2018

Duke's conclusion is based on its study of the failure events and both design and operational information including data supplied by MHPS, PI data from Bartow, information from similar units in Duke's fleet, and industry experience with the 40" blades. MHPS did not provide proprietary information concerning engineering and testing of the 40" blades but did provide engineering assistance and strain gauge data from a brief period of MHPS-led telemetry testing during December 2014. Duke provided all operational information requested by MHPS and met with MHPS multiple times to discuss both MHPS' findings and Duke's independent research and findings. This RCA report is Duke's product and presents its view of the root cause based on all inputs received.

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Appendix A: MMP5 L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	<i>Different Radial Height Relative to Bartow L-0 (About 1")</i>
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	<i>No HVOF</i>
Blade design	Original	Original	Original	<i>Attack Angle Change</i>
Material	17-4 ph	17-4 ph	17-4 ph	<i>17-4 ph</i>

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Appendix B: Empirical Data Concerning Factors which May Have Affected L-O Blades

Empirical Support for Root Cause

Operative Storm Flow

Period	Operating Hours	Normalized Blade Percent	Average Time Between Events	Normalized Count / (E) Operating Hours	Normalized Ranking
1	21,734	X	1,486	0.11	0.11
2	21,284	X	2	0.00	0.00
3	20,286	X	260	0.02	0.02
4	2,842	X	2	0.00	0.00
5	1,361	X	0	0.00	0.00

Thermal Stress (ET, AM)

Period	Operating Hours	Normalized Blade Percent	Count / (E) Operating Hours	Normalized Ranking
1	21,734	X	19	0.00
2	21,284	X	7	0.03
3	20,286	X	37	0.00
4	2,842	X	3	0.00
5	1,361	X	5	0.20

Pressure Pulses

Period	Operating Hours	Normalized Blade Percent	Avg. Head Spray Pressure (psi)	Hours of Head Spray Operation	Normalized Count / (E) Operating Hours	Normalized Ranking
1	21,734	X	3.1	1,000	0.11	0.11
2	21,284	X	2.7	7,481	0.00	0.00
3	20,286	X	3.4	400	0.00	0.00
4	2,842	X	3.3	176	0.00	0.00
5	1,361	X	3.1	0	0.00	0.00

Area of Exposure

Period	Operating Hours	Normalized Blade Percent
1	21,734	8.1%
2	21,284	6.0%
3	20,286	10.1%
4	2,842	0
5	1,361	8.1%

Blade Events

Period	Operating Hours	Normalized Blade Percent	Normalized Ranking
1	21,734	X	0.11
2	21,284	X	0.00
3	20,286	X	0.02
4	2,842	X	0.00
5	1,361	X	0.20

Period 1 Jun 2009 to Nov 2012
Period 2 Apr 2012 to Aug 2014
Period 3 Sep 2014 to Apr 2016
Period 4 May 2016 to Dec 2016
Period 5 Dec 2016 to Feb 2017

"Operative Storm Flow" notes
 - Measured number of operating hours by sub-periods of 15,000 hours (E) hours as indicated by the E column.
 - Normalized blade percent = Number of recorded events per 1000 hours of operation in a given period.
 - Normalized ranking = Data normalized against the highest value in the column, "Normalized Hours / (E) Operating Hours".

"Thermal Stress (ET, AM)" notes
 - "Counts" are defined as the number of measured events where blades were a) above 20 degrees Fahrenheit (7) greater than 20 degrees Fahrenheit (7) at the head spray thermocouples - Data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW.
 - Number of "Counts" per 1000 hours of operation in a given period.
 - Data normalized against the highest value in the column, "Counts / (E) Operating Hours".

"Pressure Pulses" notes
 - Calculated from measurements.
 - "Hours of Head Spray Operation" is a weighted value - There is a 1.00 multiplier at 50 psi and a 1.75 multiplier at 5 psi.
 - The weighted hours of head spray operation divided by the total number of operating hours - converted to a percentage value.
 - Data normalized against the highest percentage value in the column " % of Total Operating Hours".

"Area of Exposure" notes
 - In figures, the gap measure refers to both the mid-span cables and the fixed L-leaf, support cables.

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BRR 4S L-O Background

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The Bartow Combined Cycle Steam Turbine 4s (COE mid-2009) last stage blade (L-O) issues started with a routine visual inspection that lead to a forced outage in 2012 after just 3 years of in service time. Several cracks and chips were found on the blade mid-span snubbers and tip z-notches of the turbine end row. The generator end was undamaged and turbine end L-O's were replaced. The OEM concluded in a root cause investigation the cause of the issue was last stage steam flow rates beyond their design limits forcing non synchronous blade vibrations and subsequent wear and fatigue of the mating blade contact surfaces. At that time, the OEM required a limit to the IP exhaust pressure to limit steam flow into the LP section to the original design limit thus restricting output. The unit continued to run at the original design conditions until a more rugged design upgrade was developed and made available.

It is important to note that this turbine was originally designed for another project and built by the OEM, but not shipped. It was subsequently reapplied to the Bartow project with the limitations in turbine output shown on the heat balances and other documentation provided. However, it was much less clear about the exhaust flow limit the output limit implied since this pressure and flow limit is not clearly stated on the documentation given.

In spring 2015 a planned outage replaced the original design blades with blades having several improvements that included hard facing of the mid-span snubber wear surfaces. It should be noted that the original generator end blades, and the 2nd set of turbine end blades, looked to be in good condition and suitable for continued operation.

Information presented by the OEM showed test data indicating an improvement of wear rate and fatigue life by a factor of x10 with the addition of a hard face coating, as well as a significant reduction in contact stresses the revised design promised. Previous to the application of the revised blades, the OEM root cause was questioned and challenged. Two Japanese executives that made a presentation at site and their openness for questions and data presented allowed the Legacy Progress team to conclude that if we had a three year life blade and improvements could give more than x10, the goal a reasonable life (> 15 yrs) was very likely. A contract for procuring and testing this revised upgraded blade also added protection and reduced risk with a 6 yr warranty 3 yr full remainder prorated, a significant upgrade from 1 or 2 yr full warranty. This seemed an adequate choice to justify the decision to plan and schedule this 2015 outage with the upgraded blade.

The test plan for the new blades included strain gage testing in the OEM facility, which we witnessed, and in-situ strain gage testing at site with full load steam. All steps reasonable and practical were taken to assure the design was going to be successful, and the team performed due diligence with the choice to select the redesigned blade and validate it without waiting 3 years for run experience. The testing did reveal an "avoidance zone" or combination of steam flow and condenser backpressures that was a driver for blade stresses above desirable levels. When the unit was returned to service and released for operation with this "avoidance zone", it was intended that the unit not be run with these combinations of flow and backpressures.

In early spring 2016, an inspection that was expected to be routine and have no findings revealed damage at a blade tip z-notch that rendered the unit at a high risk to return to service by the OEM. The blades were

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replaced in May 2016 with a second OEM design modification that included adding more hard facing to the tip z-notch contact surfaces.

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The unit restarted in June 2016 and ran until July 2016 when a step change in vibration of approximately 0.5 mils at the LP bearings occurred. The unit continued to run and an additional small step change occurred in Aug 2016. The OEM was consulted and they felt the vibration changes were due to changes in bearing stiffness. The Duke team was not completely comfortable with the OEM's explanation and while we felt that rotor mass loss may not be likely, it was possible, and therefore the unit needed to be shut down for a visual inspection. Commercial load demands, two hurricanes and other unit outages postponed this inspection until mid-Oct 2016.

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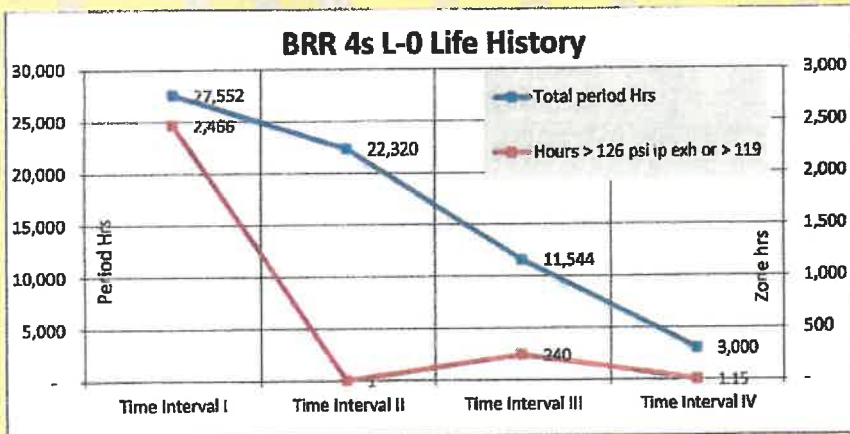
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This recent inspection revealed the cause of the vibration changes to be significant mass loss of three separate L-0 blade tip z-notches - one on the turbine end row, and two on the generator end row. In addition, at least one mid-span snubber has failed. The data indicate one of the blades only ran 30 days prior to falling.

The expected blade life predictions of the latest blade configuration compared to the actual field experience is the driver for the study in attachment A of steam turbine output and operating pressures versus time. There is one particular fact and clear apparent path forward that can be seen in this data. The Table below from the attachment presents the fact that the more we modified the blades, the shorter the time before contact surface failure despite the fact we have continued operate the unit with lower steam flows that fall mostly within the OEM limits for the original design.



Inspection of the data reveal that the original design in time intervals 1 and 2 only had the mid-span snubber failure of the original turbine end (TE) blades - and the 1st time interval nearly 2500 hours of operation was above the OEM limit. In time interval 2, no failures occurred and there was only 1 hours of operation slightly above the limit. This means that the generator end (GE) blades ran nearly 50,000 hours with no failures.

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This is in contrast to time interval 3 where failures occurred after only 11.5 hrs of operation with only 240 hours above the original limit – and interval 4 with only 3 hrs of operation and just over only 1 hour above the original flow limit. The data clearly suggest that returning to the original design, and limiting the IP exhaust pressure to 125 psig (not sure I'm reading that right off the graph), which will give approximately 400 to 605 MW with 4x1 operation, will give much more acceptable life than the modified design.

Summary of Data

While there are many significant points and facts to be concluded from the data being presented, a glaring fact that surfaces is the more we improved the blade design (two modifications, three versions tested) and simultaneously reduce the time at excessive flows, the shorter the blade service interval has become. It was never obvious earlier in the spring 2016 failure because the time operations exceeded the pressure was the focus of the second yet incomplete RCA. No one knew the first service run had so many hours above the later imposed pressure limit.

While in the period I there were 33K hrs available and 2600 hrs with high pressure operation. There were no blades found with complete g-notch lug loss and no step changes in vibration were encountered.

Compare this to period III with 11k hrs and 240 hrs with high pressure. This is the first design modification compared to the original design we were trying to improve. The life decreased by x 1/3 rather than increase by x10. The high pressure hours did decrease from 9% of the time period to 2%, but the blade service life still decreased. This is counter to the expected result.

In period IV the unit ran 3k hrs with 1.15 hrs at high pressure. This is the second design modification. The life decreased to ~ x 1/10 not x10 as advertised. If you consider the unit actually failed a blade 30 days after restart when the vibration changed ~ 700 hours the decrease in life is even less x 1/10 to approx. x 0.2. Or effectively the second design modification, with pressure restrictions, gave 2% of the life of the original design with no pressure restriction.

For these reasons the recommended direction on the current repair (fall 2016) is to return to the original blade design (no hard facing) with reasonable operational restrictions on steam flows and pressure limits. These restrictions need to be part of the control logic and not an operator or supervision option to interpret.

If this style blade is not quickly available the option of inspecting and installing the blades removed in 2012 should be evaluated against an extended outage waiting for blades. This is not the first recommendation.

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Opinion

These facts supported by actual experienced field data suggest the proposed OEM root cause may not be inclusive of all interactions possible. It also suggests the following points need to be investigated for a better RCA

- Quality of coating (workmanship)
 - o Is coating not adhering. Some evidence in visuals to date
 - o Is process changing fatigue strength of base material
 - o Is coating non uniform allowing higher partial face contact stresses
 - o other
- Quality of blade assembly (workmanship)
 - o Are the high vibrations we experience on return to service causing additional blade stresses. MHI has low speed field balanced twice now with both attempts resulting in more Low pressure turbine vibration post outage than pre outage.
 - o Are the hardened faces being damaged as blades are being hammered in the fan sequence.
 - o Other
- Design
 - o Did blade tuning change design modifications and a higher frequency mode get introduced.
 - o Is there some yet to be found driver for the fatigue the design changes are not considering and life is becoming shorter.
 - o Has there been changes to other manufacturing processes, such as areas of the blade surface that are shot peened? (There appears to be an unpeened area in the fillet of the lug which is not apparent on the original blades – this is near where the cracking occurs).
 - o Does the blade material meet spec? Hardness, tensile/ultimate, etc.
 - o Other

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Executive Summary

Duke and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 12 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation. During a presentation given at Bartow Station on 15 March 2017, MHPS suggested the sole root cause for Period 3 (Dec 2014-Mar 2016) was "operation in the avoidance zone". While Duke Engineering would agree that operation in the avoidance zone is certainly a *contributing factor* to the shroud chipping experienced in Period 3, it is not the only contributing factor that should be considered when trying to determine root cause for the Period 3 Bartow Unit 4S event, or any of the previous/subsequent events for that matter.

After months of study, Duke Engineering believes the following to be the most significant contributing factors toward root cause of the history of Bartow Unit 4S L-0 events.

- Low Pressure (LP) Turbine Back-End Loading (>15,000 lb./hr./ft.²)
- Blending Operations
- Hood Spray Operations
- Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches
- Configuration (e.g. Hard-Facing on Z-Notches)

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above.

Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Notch failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

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Root Cause Contributing Factors

LP Turbine Back-End Loading (>15,000 lb./hr./ft.²)

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data analysis – learned (and made it known to Duke) that a significant contributing factor toward root cause of the L-0 blade failures was extremely high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" transient conditions.

While Duke Engineering agrees that back-end loading should be considered a significant contributing factor toward root cause, one cannot definitively conclude that it has been the root cause of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern.

Blending Operations

(insert text)

Hood Spray Operations

(insert text)

Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches

(insert text)

Configuration (Hard-Facing on the Z-Notches)

(Insert text)

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Duke Engineering's believes that MHPS's conclusions represent contributing factors in the failures; therefore, Duke is not in concurrence with the recommended RCA conclusion. MHPS and Duke have been working together, and continue to work together, to collect data and evidence to determine the drivers behind these L-0 blade failures. Data suggests that there are *several contributing factors, none of which have been quantified conclusively to determine the root cause to any particular failure event.*

There are five periods of interest:

Period 1: Concluded in 2012 with approximately 34 months of operation with Type 1 L-0's in service.

Five turbine end (TE) L-0 blades were found to have broken snubbers, the L-0 blades were replaced.

During this period the blades operated in (what MHPS would define during the transition from Period 2 into Period 3 as) the avoidance zone for 2,466 hours with no operating restrictions placed on the ST.

No RCA was conducted as Duke worked with MHPS and was willing to have MHPS provide and eventually install what was thought to be the solution to the issue with new design blades (installed in Fall 2014).

Period 2: Concluded in 2014 with approximately 28 months of operation with Type 1 L-0's in service. This was a planned outage to replace the L-0 blades with an Enhanced/More Robust Blade (Type 3 v1).

The IP Exhaust Pressure operated at a limit of 118 psig during period 2.

Blade telemetry instrumentation was also installed during the Period 2 outage to measure blade stresses and determine the limits of the avoidance zone in operation (performed by crossing the avoidance zone in operation and measuring blade stresses).

No RCA was required.

Period 3: Concluded in the spring of 2016 with approximately 17 months of operation with Type 3 (v1) L-0's in service. This was a forced outage as a result of several blades with broken Z-lock interfaces on both generator end (GE) and turbine end (TE) L-0's.

After commissioning the blades operated in the avoidance zone for ~20 hrs to further refine the avoidance zone. Operations restricted output by limiting IP Exhaust pressure to 126 psig (based on strain gauge data). Blade strain gage data also shows high stress areas in operation outside the avoidance zone (no operating limitations placed around these areas by MHPS).

MHPS Engineering added stellite hard facing to the Z-lock contact faces to the newly installed blades as a measure to prevent wear and breakage.

The RCA is currently inconclusive from data and findings, but several contributing factors have been determined.

Note: At the onset of Period 3, per MHPS Engineering, short term operation – i.e. 10-20 minutes per occurrence – within the avoidance zone was allowable under certain operating ranges for both condenser backpressure and IP exhaust pressure during, for example, peak power seasons in summer. Over the course of time and subsequent L-0 events, MHPS Engineering amended and restated their technical disposition to express that operation within the avoidance zone should be prohibited altogether.

Commented [JRS1]: I think we should add because we worked with MHPS to design and install what was thought to be the solution to the issue with new design blades installed in fall 2014.

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Period 4: Concluded in the fall of 2016 with approximately 5 months of operation with Type 3 (v2) L-0's in service. This was a forced outage as a result of several L-0 blades with broken Z-lock interfaces and missing airfoil material. Inspection of the Z-lock area showed less than desirable contact on the Z-lock surface (~10% contact vs ~60% contact). The Z-lock surface needs to properly contact to obtain the desired dampening effect during operation. During this period the blades operated in the avoidance zone for 1.15 hours with additional operating limitations of 119 psig in IP exhaust pressure. Several L-0 blades from Period 1, 3, and 4 were measured to compare geometry. Scans show wide range of geometry from manufacturing; it is unknown if these deviations are within design expectancy or not (MHPS has requested blades for scanning to compare – in process). MHPS is evaluating if the additional stellite coating on the Z lock promoted a loss of dampening. Since this failure mode was significantly different than any in the past or since this period, i.e. complete loss of a Z-lock tip and air foil section, and the crack started at the blades high point for stress the design may have been compromised because of hard facing on all mating surfaces. The RCA is currently inconclusive, the application of the HVOF coating on the Z-lock surface appear to be one of the leading factors in the failure. The replacement blades going into Period 5 reverted back to the Type 1 design. The Station also installed DCS logic to trigger alarms before operation occurs in the Avoidance zone.

Period 5: Concluded in the spring of 2017 with approximately 2 months of operation with Type 1 L-0's in service. This was a forced outage that was a result of several blades with broken Z-lock interfaces and snubbers on the Generator End (GE) L-0 blades. During this period the blades operated in the avoidance zone for 0 hours with additional operating limitations of 111.1 psig in IP exhaust pressure. For the first time, Duke Engineering identified blending as a possible contributing factor to the RCA. "Blending steam" is a common occurrence with combined cycle applications. One example of a suspect blend transient is evidence of measured water hammer event(s) in piping networks that dump into the condenser. The shock wave developed by a suspect blend transient does enter the condenser hotwell, however the impact of these type events on the L-0 blades is analytically unknown. Work is underway to determine if blend transients can be correlated to blade telemetry data from 2014/15.

Note: "Blending In" steam involves integrating steam production from a specific CT/HRSG train into the ST. "Blending Out" steam involves bypassing steam from the ST to the condenser as a particular CT/HRSG train transfers from combined cycle to simple cycle operations (or offline).

The RCA is still underway with no conclusions developed from data and findings.

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Appendix A: Bartow L-O Event Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-O Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	450 MW (420 Nameplate)	420 MW per MHI	450 MW	450 MW	390 MW
Operating Restrictions	None	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exceeded hrs	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,320 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 3,000 hrs)	0 hrs
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *z-lock and airfoils	0 TE / 8 GE
Worn Z-locks	not captured		high degree of wear observed		high degree of wear observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) & continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mph LP exhaust flow).	Not a forced outage. Outage planned to upgrade to "heavy duty" blades. Some blade damage was observed from removed service blades. Blade telemetry instrumentation installed (Dec 21 - Dec 24, 2014)	Blade telemetry testing; intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed. Blade telemetry data also shows higher stress areas in operation outside the avoidance zone based on blade strain data (no operating limitations placed around these areas by MHPS), data indicates we operated in these zones "X" hrs during the period.	Blade loss of material, crack initiation in high stress area of airfoil. Stellite hard facing had been added to the blade z-lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection. At first, MHPS did not support this recommendation, nor did they support the idea that "loss of mass" had occurred.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-O events. Jan 2017 "loss of mass" event - blade fragment projectile traveled through the LP turbine rupture disk diaphragm. Dental mold impression of failure surfaces indicate ~10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber). Confirmation from the Harris met lab evaluation should help determine cracking mechanism
Information shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested. MHPS learned through Duke Engineering (Intentional) that we were investigating blending and its impact to the Condenser/ST MHPS RCA team for the first time learned what "blending in" and "blending out" meant.

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Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	New
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	Height same as Bartow
Z-Lock	No HVOF	No HVOF	HVOF applied	No HVOF
Blade design	Orig.	Orig.	Orig.	Attack Angle change
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	In commissioning (~1yr)
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

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Executive Summary

Duke and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 12 months to determine what has caused the Bartow Unit 4S L-O blades to crack and break during operation. During a presentation given at Bartow Station on 15 March 2017, MHPS suggested the sole root cause for Period 3 (Dec 2014-Mar 2016) was "operation in the avoidance zone". While Duke Engineering would agree that operation in the avoidance zone is certainly a *contributing factor* to the shroud chipping experienced in Period 3, it is not the only contributing factor that should be considered when trying to determine root cause for the Period 3 Bartow Unit 4S event, or any of the previous/subsequent events for that matter.

After months of study, Duke Engineering believes the following to be the most significant contributing factors toward root cause of the history of Bartow Unit 4S L-O events.

- Low Pressure (LP) Turbine Back-End Loading (>15,000 lb./hr./ft.²)
- Blending Operations
- Hood Spray Operations
- Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches
- Configuration (e.g. Hard-Facing on Z-Notches)

This technical paper will speak briefly of the history of L-O blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above.

Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating

Since commissioning there have been five (5) events triggered by L-O blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Notch failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-O blade in efforts to address the failures (see Appendix B for L-O modifications). To date, the modifications have not resulted in improved reliability or performance of the L-O blades in service at Bartow. The number of blade failures and problems with ST L-O blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-O fleet. The most common reported issue from the MHPS 40" L-O blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-O rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

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Root Cause Contributing Factors

LP Turbine Back-End Loading (>15,000 lb./hr./ft.²)

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data analysis – learned (and made it known to Duke) that a significant contributing factor toward root cause of the L-0 blade failures was extremely high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40” L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40” L-0 fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an “avoidance zone” chart with instructions from MHPS not to run to the right side of the curve – the lone exception being “brief” transient conditions.

While Duke Engineering agrees that back-end loading should be considered a significant contributing factor toward root cause, one cannot definitively conclude that it has been the root cause of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the “avoidance zone” of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

As for Period 3 there were only approximately 240 hours of operation in the avoidance zone, of which approximately 11 hours occurred during the instrumented test by MHPS in December of 2014. Even with the greatly reduced amount of high flow hours for Period 3 as compared to Period 1 (a factor of 10 fewer hours for Period 3), a high amount of wear and distress was seen on the z-notch contact surfaces. While the amount of z-notch wear is not quantified for Period 1 and 3, photographic evidence suggests that the amount of wear is similar. It therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern.

Blending Operations

During the most recent root cause analysis, the team expanded its view of turbine operations to all aspects that might impact the L-0 blades. Since the design of the condenser includes spargers or “dump tubes” for the hot reheat (HRH) and low pressure (LP) bypass steam flows from each of the four CTs, and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink was developed that allows large amounts of data stored in PI to be quickly reviewed for each time Period. Blends that meet the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. The process relies on extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values over 20

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degrees F when a CT is being blended off or on the steam turbine and the steam turbine output is greater than 50 mw. The limits of 20 F and 50 mw were selected as these are good indications that the blend steam had either higher or lower enthalpy than intended for the design of the spraying system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow a comparison of the number of higher energy blends that occurred in each period, and it allows the team to quickly identify times to look at additional blend parameters.

Below is a quick comparison of the number blends that meet the criteria for Periods 1 thru 5.

	Number of days in Period	Number of blends meeting criteria
Period 1	1185 days	13*
Period 2	973 days	7
Period 3	482 days	31**
Period 4	127 days	3
Period 5	68 days	5

*Includes the time period during commissioning from 1/1/2009 to 6/1/2009

**Excludes 6 blends that meet criteria during strain gauge testing in December 2014

Hood Spray Operations

The RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psi condensate pressure to the design pressure for the sprays of 50 psig. Review of MHPS provided instructions requires use of hood sprays under the following conditions:

- Speed greater than 600 rpm and load less than 10 mw
- Hood spray thermocouple reading greater than 160 F

During review of the hood spray data, it became clear that additional operation besides the above had been programmed into the DCS since commissioning. In addition to the above, hood sprays were programmed to turn on anytime blending took place (similar to the way the curtain sprays are programmed). No explanation for why this was done has been found. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended. A review of hood spray thermocouple data shows they rarely reach 160 F during normal operation and never over 165 F. Higher temperatures are sometimes seen after a shutdown or trip when the temperature in the exhaust increases, most likely due to the hot LP casing and some windage. No temperatures over 201 F were found (one very brief reading of 1040 F was an instrument issue).

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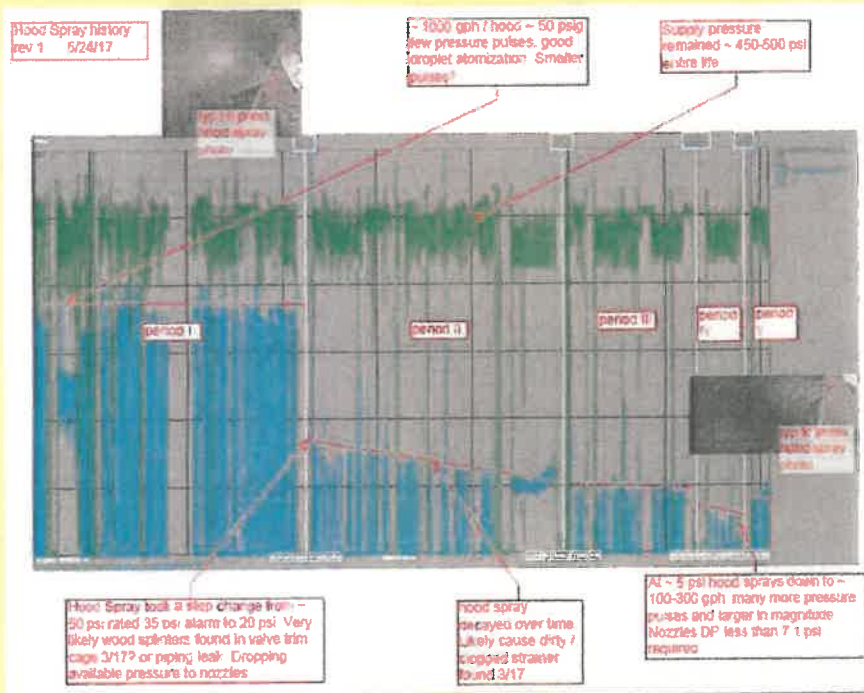
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Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the valve in spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the valve had filled with debris in prior years.

The chart below shows what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will have reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-O blades might see as large water droplets evaporate in the exhaust stream.



Curtain Spray Operations

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Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches

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Configuration (Hard-Facing on the Z-Notches)

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Duke Engineering's believes that MHPS's conclusions represent contributing factors in the failures; therefore, Duke is not in concurrence with the recommended RCA conclusion. MHPS and Duke have been working together, and continue to work together, to collect data and evidence to determine the drivers behind these L-0 blade failures. Data suggests that there are several contributing factors, none of which have been quantified conclusively, to determine the root cause to any particular failure event.

There are five periods of interest:

Period 1: Concluded in 2012 with approximately 34 months of operation with Type 1 L-0's in service.

Five turbine end (TE) L-0 blades were found to have broken snubbers, the L-0 blades were replaced.

During this period the blades operated in (what MHPS would define during the transition from Period 2 into Period 3 as) the avoidance zone for 2,466 hours with no operating restrictions placed on the ST.

No RCA was conducted as Duke worked with MHPS and was willing to have MHPS provide and eventually install what was thought to be the solution to the issue with new design blades (Installed in Fall 2014).

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Period 2: Concluded in 2014 with approximately 28 months of operation with Type 1 L-0's in service. This was a planned outage to replace the L-0 blades with an Enhanced/More Robust Blade (Type 3 v1).

The IP Exhaust Pressure operated at a limit of 118 psig during period 2.

Blade telemetry instrumentation was also installed during the Period 2 outage to measure blade stresses and determine the limits of the avoidance zone in operation (performed by crossing the avoidance zone in operation and measuring blade stresses).

No RCA was required.

Period 3: Concluded in the spring of 2016 with approximately 17 months of operation with Type 3 (v1)

L-0's in service. This was a forced outage as a result of several blades with broken Z-lock interfaces on both generator end (GE) and turbine end (TE) L-0's.

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After commissioning the blades operated in the avoidance zone for ~20 hrs to further refine the avoidance zone. Operations restricted output by limiting IP Exhaust pressure to 126 psig (based on strain gauge data). Blade strain gage data also shows high stress areas in operation outside the avoidance zone (no operating limitations placed around these areas by MHPS).

MHPS Engineering added stellite hard facing to the Z-lock contact faces to the newly installed blades as a measure to prevent wear and breakage.

The RCA is currently inconclusive from data and findings, but several contributing factors have been determined.

Note: At the onset of Period 3, per MHPS Engineering, short term operation – i.e. 10-20 minutes per occurrence – within the avoidance zone was allowable under certain operating ranges for both condenser backpressure and IP exhaust pressure during, for example, peak power seasons in summer. Over the course of time and subsequent L-O events, MHPS Engineering amended and restated their technical disposition to express that operation within the avoidance zone should be prohibited altogether.

Period 4: Concluded in the fall of 2016 with approximately 5 months of operation with Type 3 (v2) L-O's inservice. This was a forced outage as a result of several L-O blades with broken Z-lock interfaces and missing airfoil material. Inspection of the Z-lock area showed less than desirable contact on the Z-lock surface (~10% contact vs ~60% contact). The Z-lock surface needs to properly contact to obtain the desired dampening effect during operation.

During this period the blades operated in the avoidance zone for 1.15 hours with additional operating limitations of 119 psig in IP exhaust pressure.

Several L-O blades from Period 1, 3, and 4 were measured to compare geometry. Scans show wide range of geometry from manufacturing; it is unknown if these deviations are within design expectancy or not (MHPS has requested blades for scanning to compare – in process).

MHPS is evaluating if the additional stellite coating on the Z lock promoted a loss of dampening. Since this failure mode was significantly different than any in the past or since this period, i.e. complete loss of a Z-lock tip and air foil section, and the crack started at the blades high point for stress the design may have been compromised because of hard facing on all mating surfaces. The RCA is currently inconclusive, the application of the HVOF coating on the Z-lock surface appear to be one of the leading factors in the failure. The replacement blades going into Period 5 reverted back to the Type 1 design.

The Station also installed DCS logic to trigger alarms before operation occurs in the Avoidance zone.

Period 5: Concluded in the spring of 2017 with approximately 2 months of operation with Type 1 L-O's in service. This was a forced outage that was a result of several blades with broken Z-lock interfaces and snubbers on the Generator End (GE) L-O blades.

During this period the blades operated in the avoidance zone for 0 hours with additional operating limitations of 111.1 psig in IP exhaust pressure.

For the first time, Duke Engineering identified blending as a possible contributing factor to the RCA. "Blending steam" is a common occurrence with combined cycle applications. One example of a suspect blend transient is evidence of measured water hammer event(s) in piping networks that dump into the condenser. The shock wave developed by a suspect blend transient does

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enter the condenser hotwell, however the impact of these type events on the L-0 blades is analytically unknown. Work is underway to determine if blend transients can be correlated to blade telemetry data from 2014/15.

Note: "Blending In" steam involves integrating steam production from a specific CT/HRSG train into the ST. "Blending Out" steam involves bypassing steam from the ST to the condenser as a particular CT/HRSG train transfers from combined cycle to simple cycle operations (or offline).

The RCA is still underway with no conclusions developed from data and findings.

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Appendix A: Bartow L-0 Event Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	450 MW (420 Nameplate)	420 MW per MHI	450 MW	450 MW	390 MW
Operating Restrictions	None	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exceedance	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,320 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 3,000 hrs)	0 hrs
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 3 GE	1 TE / 2 GE *z-lock and airfoils	0 TE / 8 GE
Worn Z-locks	not captured		high degree of wear observed		high degree of wear observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 5x1 heat balance) & continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mph LP exhaust flow).	Not a forced outage. Outage planned to upgrade to "heavy duty" blades. Some blade damage was observed from removed service blades. Blade telemetry instrumentation installed (Dec 21 - Dec 24, 2014)	Blade telemetry testing; intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed. Blade telemetry data also shows higher stress areas in operation outside the avoidance zone based on blade strain data (no operating limitations placed around these areas by MHPS), data indicates we operated in these zones "X hrs during the period.	Blade loss of material, crack initiation in high stress area of airfoil. Stellite hard facing had been added to the blade z-lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection. At first, MHPS did not support this recommendation, nor did they support the idea that "loss of mass" had occurred.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events. Jan 2017 "loss of mass" event - blade fragment projectile traveled through the LP turbine rupture disk diaphragm Dental mold impression of failure surfaces indicate ~10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber). Confirmation from the Harris met lab evaluation should help determine cracking mechanism
Information shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested. MHPS learned through Duke Engineering (Intentional) that we were investigating blending and its impact to the Condenser/ST. MHPS RCA team for the first time learned what "blending in" and "blending out" meant.

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Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	New
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Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	Height same as Bartow
Z-Lock	No HVOF	No HVOF	HVOF applied	No HVOF
Blade design	Orig.	Orig.	Orig.	Attack Angle change
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	In commissioning (~1yr)
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

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Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0blade failures is that the OEM designed blades were inadequate for the operating conditions with which they were subjected.

Duke Engineering believes the root cause for Periods 1-5 involves more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.². Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. Today, there is agreement between both parties that there is not just one simple root cause.

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After months of study, Duke Engineering believes the following to be the most significant contributing factors toward root cause of the history of Bartow Unit 4S L-0 events.

- Low Pressure (LP) Turbine Excessive Steam Flow
- Thermal Distress at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operations
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening (e.g. Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces)
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the telemetry test conducted during December 2014 – blade response data that is then extrapolated to theorize potential root cause for blade failures at the mid-span snubber, shroud Z Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution (e.g. redesigned blades) for the Bartow LP section and subsequent field measurements taken following various operating configurations/scenarios that are integral to unrestricted 4 x 1 combined cycle operation will be necessary to confirm the contributing factor postulations. In other words, the correctness of the Duke and/or MHPS root cause position(s) can only be confirmed with the successful field operation of the unit.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above.

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Root Cause Contributing Factors

LP Turbine Back-End Loading (>15,000 lb./hr./ft.²)

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data analysis – learned (and made it known to Duke) that a significant contributing factor toward root cause of the L-0 blade failures was extremely high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an "avoidance zone" chart with instructions from MHPS not to turn to the right side of the curve – the lone exception being "brief" transient conditions.

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With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern.

Blending Operations – Thermal Distress (dT_{SH}/dt) at L-0 Exit

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to all aspects that might impact the L-0 blades. Since the design of the condenser includes spargers, or "dump tubes", for the hot reheat (HRH) and LP bypass steam flows from each of the four CTs, and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink was developed that allows large amounts of data stored in PI to be quickly reviewed for each time Period. Blends that meet the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. The process relies on extracting PI data, calculating a value of superheat at the hood

Commented [PVC2]: This is what I recall - but we need the photos to prove this otherwise we can't say it.

Commented [PVC3]: However, MHPS has not done any review and released us to go to higher LP inlet pressures/flows.

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spray thermocouples, calculating a rate of change of that value, and flagging those values over 20 degrees F when a CT is being blended off or on the steam turbine and the steam turbine output is greater than 50 MW. The limits of 20 degrees F and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow a comparison of the number of higher energy blends that occurred in each period, and it allows the team to quickly identify times to look at additional blend parameters.

Below is a quick comparison of the number blends that meet the criteria for Periods 1 thru 5.

	Number of days in Period	Number of blends meeting criteria
Period 1	1185 days	13*
Period 2	973 days	7
Period 3	482 days	31**
Period 4	127 days	3
Period 5	68 days	5

*Includes the time period during commissioning from 1/1/2009 to 6/1/2009

**Excludes 6 blends that meet criteria during strain gauge testing in December 2014

Hood Spray Operations – Pressure Pulses

The RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

Review of MHP5-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

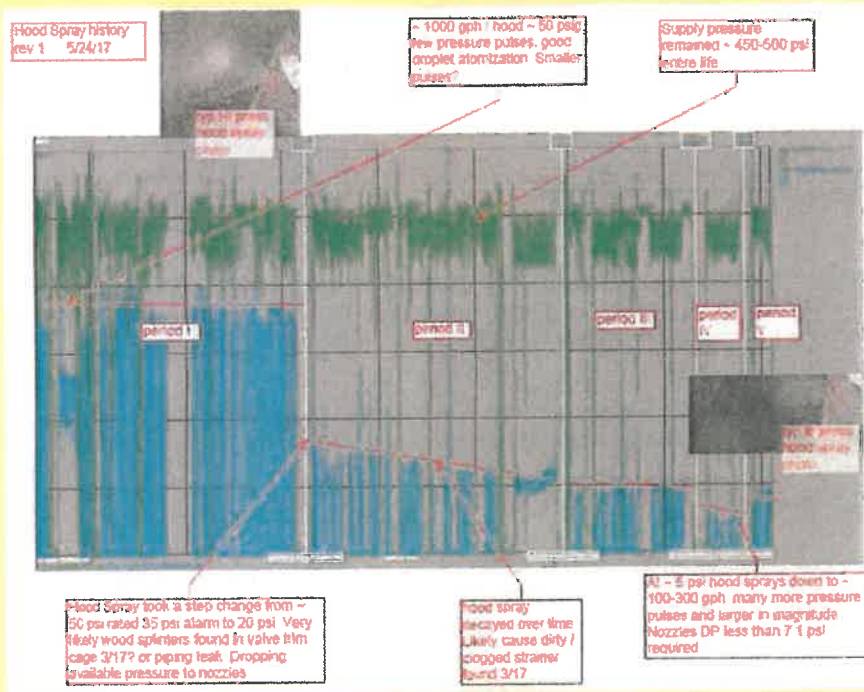
During review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or trip when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrument issue).

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Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the valve had filled with debris in prior years.

Commented [JCE4]: Which valve is this – The control valve mentioned in the above paragraph?
Commented [JCE5]: Same comment as JCE4.

The chart below demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-O blades might see as large water droplets evaporate in the exhaust stream.



Curtain Spray Operations

(Insert text)

Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches

(Insert text)

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Configuration (Hard-Facing on the Z-Notches)

(insert text)

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Duke Engineering's believes that MHPS's conclusions represent contributing factors in the failures; therefore, Duke is not in concurrence with the recommended RCA conclusion. MHPS and Duke have been working together, and continue to work together, to collect data and evidence to determine the drivers behind these L-0 blade failures. Data suggests that there are several contributing factors, none of which have been quantified conclusively to determine the root cause to any particular failure event.

There are five periods of interest:

Period 1: Concluded in 2012 with approximately 34 months of operation with Type 1 L-0's in service.

Five turbine end (TE) L-0 blades were found to have broken snubbers, the L-0 blades were replaced.

During this period the blades operated in (what MHPS would define during the transition from Period 2 into Period 3 as) the avoidance zone for 2,466 hours with no operating restrictions placed on the ST.

No RCA was conducted as Duke worked with MHPS and was willing to have MHPS provide and eventually install what was thought to be the solution to the issue with new design blades (Installed in Fall 2014).

Period 2: Concluded in 2014 with approximately 28 months of operation with Type 1 L-0's in service. This was a planned outage to replace the L-0 blades with an Enhanced/More Robust Blade (Type 3 v1).

The IP Exhaust Pressure operated at a limit of 118 psig during period 2.

Blade telemetry instrumentation was also installed during the Period 2 outage to measure blade stresses and determine the limits of the avoidance zone in operation (performed by crossing the avoidance zone in operation and measuring blade stresses).

No RCA was required.

Period 3: Concluded in the spring of 2016 with approximately 17 months of operation with Type 3 (v1) L-0's in service. This was a forced outage as a result of several blades with broken Z-lock Interfaces on both generator end (GE) and turbine end (TE) L-0's.

After commissioning the blades operated in the avoidance zone for ~20 hrs to further refine the avoidance zone. Operations restricted output by limiting IP Exhaust pressure to 126 psig (based on strain gauge data). Blade strain gage data also shows high stress areas in operation outside the avoidance zone (no operating limitations placed around these areas by MHPS).

MHPS Engineering added stellite hard facing to the Z-lock contact faces to the newly installed blades as a measure to prevent wear and breakage.

The RCA is currently inconclusive from data and findings, but several contributing factors have been determined.

Note: At the onset of Period 3, per MHPS Engineering, short term operation – i.e. 10-20 minutes per occurrence – within the avoidance zone was allowable under certain operating ranges for both condenser backpressure and IP exhaust pressure during, for example, peak power seasons in summer. Over the course of time and subsequent L-0 events, MHPS Engineering amended and restated their technical disposition to express that operation within the avoidance zone should be prohibited altogether.

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Period 4: Concluded in the fall of 2016 with approximately 5 months of operation with Type 3 (v2) L-O's inservice. This was a forced outage as a result of several L-O blades with broken Z-lock interfaces and missing airfoil material. Inspection of the Z-lock area showed less than desirable contact on the Z-lock surface (~10% contact vs ~60% contact). The Z-lock surface needs to properly contact to obtain the desired dampening effect during operation. During this period the blades operated in the avoidance zone for 1.15 hours with additional operating limitations of 119 psig in IP exhaust pressure. Several L-O blades from Period 1, 3, and 4 were measured to compare geometry. Scans show wide range of geometry from manufacturing; it is unknown if these deviations are within design expectancy or not (MHPS has requested blades for scanning to compare – in process). MHPS is evaluating if the additional stellite coating on the Z lock promoted a loss of dampening. Since this failure mode was significantly different than any in the past or since this period, i.e. complete loss of a Z-lock tip and air foil section, and the crack started at the blades high point for stress the design may have been compromised because of hard facing on all mating surfaces. The RCA is currently inconclusive, the application of the HVOF coating on the Z-lock surface appear to be one of the leading factors in the failure. The replacement blades going into Period 5 reverted back to the Type 1 design. The Station also installed DCS logic to trigger alarms before operation occurs in the Avoidance zone.

Period 5: Concluded in the spring of 2017 with approximately 2 months of operation with Type 1 L-O's in service. This was a forced outage that was a result of several blades with broken Z-lock interfaces and snubbers on the Generator End (GE) L-O blades. During this period the blades operated in the avoidance zone for 0 hours with additional operating limitations of 111.1 psig in IP exhaust pressure. For the first time, Duke Engineering identified blending as a possible contributing factor to the RCA. "Blending steam" is a common occurrence with combined cycle applications. One example of a suspect blend transient is evidence of measured water hammer event(s) in piping networks that dump into the condenser. The shock wave developed by a suspect blend transient does enter the condenser hotwell, however the impact of these type events on the L-O blades is analytically unknown. Work is underway to determine if blend transients can be correlated to blade telemetry data from 2014/15.

Note: "Blending In" steam involves integrating steam production from a specific CT/HRSG train into the ST. "Blending Out" steam involves bypassing steam from the ST to the condenser as a particular CT/HRSG train transfers from combined cycle to simple cycle operations (or offline).

The RCA is still underway with no conclusions developed from data and findings.

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Appendix A: Bartow L-0 Event Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	450 MW (420 Nameplate)	420 MW per MHI	450 MW	450 MW	390 MW
Operating Restrictions	None	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig limit on IP Exh
Blade Over speed condition	Over speed testing in MPG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exceedance	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,320 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 3,000 hrs)	0 hrs
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *z-lock and airfoils	0 TE / 8 GE
Worn Z-locks	not captured		high degree of wear observed		high degree of wear observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) & continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).	Not a forced outage. Outage planned to upgrade to "heavy duty" blades. Some blade damage was observed from removed service blades. Blade telemetry instrumentation installed ("Dec 21 - Dec 24", 2014)	Blade telemetry testing; intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed. Blade telemetry data also shows higher stress areas in operation outside the avoidance zone based on blade strain data (no operating limitations placed around these areas by MHPS), data indicates we operated in these zones "X hrs during the period.	Blade loss of material, crack initiation in high stress area of airfoil. Stellite hard facing had been added to the blade z-lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection. At first, MHPS did not support this recommendation, nor did they support the idea that "loss of mass" had occurred.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events. Jan 2017 "loss of mass" event -- blade fragment projectile traveled through the LP turbine rupture disk diaphragm. Dental mold impression of failure surfaces indicate "J0"7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber). Confirmation from the Harris met lab evaluation should help determine cracking mechanism
Information shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested. MHPS learned through Duke Engineering (intentional) that we were investigating blending and its impact to the Condenser/ST. MHPS RCA team for the first time learned what "blending in" and "blending out" meant.

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Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 3
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	Height same as Bartow
Z-Lock	No HVOF	No HVOF	HVOF applied	No HVOF
Blade design	Orig.	Orig.	Orig.	Attack Angle change
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	In commissioning (~1yr)
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

Deleted: New

Period	Excessive Steam Flow	Pressure Pulse from Hood Spray	Thermal Distress at L-0 Exhaust (dTemp/dtime)	Loss of Dampening	Geometry	Other Mechanisms
1	X		X		X	
2		X	X		X	
3	X	X	X		X	
4				X	X	
5		X	X		X	

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Executive Summary

Duke and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 12 months to determine what has caused the Bartow Unit 4S L-O blades to crack and break during operation. During a presentation given at Bartow Station on 15 March 2017, MHPS suggested the sole root cause for Period 3 (Dec 2014-Mar 2016) was "operation in the avoidance zone". While Duke Engineering would agree that operation in the "avoidance zone" is certainly a *contributing factor* to the shroud chipping experienced in Period 3, it is not the only driving mechanism that should be considered when trying to determine root cause for the Period 3 Bartow Unit 4S event, or any of the previous/subsequent events for that matter.

After months of study, Duke Engineering believes the following to be the most significant contributing factors toward root cause of the history of Bartow Unit 4S L-O events.

- Low Pressure (LP) Turbine Excessive Steam Flow
- Thermal Distress at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operations
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Loss of Dampening (e.g. Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces)

This technical paper will speak briefly of the history of L-O blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above.

Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

Commented [PVC1]: For period 3 only

Since commissioning there have been five (5) events triggered by L-O blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-O blade in efforts to address the failures (see Appendix B for L-O modifications). To date, the modifications have not resulted in improved reliability or performance of the L-O blades in service at Bartow. The number of blade failures and problems with ST L-O blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-O fleet. The most common reported issue from the MHPS 40" L-O blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-O rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

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Bartow 4S Root Cause Analysis – Evaluation of Contributing Factors

- LP Turbine Back-End Loading (>15,000 lb./hr./ft.²)
- Blending Operations
- Hood Spray Operations
- Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches
- Configuration (e.g. Hard-Facing on Z-Notches)

Executive Summary – written last to summarize...

Brief History – Copy/Paste and Add to what Ben wrote in his summary to Jeff Swartz/Tony Salvarazza (03/29)

Briefly address the exhaustive analysis of potential contributing factors (give examples of the ones that didn't make the cut) and then lead in to the discussion of the primary 5.

LP Turbine Back-End Loading (>15,000 lb./hr./ft.²)

Talk about how this has had an effect (or not) on the unit across the different periods of operation.

Blending Operations

We've had bad blends during all 5 periods of operation.

Hood Spray Operations

We've had consistent through the 5 periods with the exception of the operating feed pressure, which began to decay over time beginning in Period 2 (which was indicative of poor atomization).

Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches

Based on the quality documentation received from OEM , as well as from our own measurements, we've noted a wide range of variation contact surface parallelism, or lack thereof. Observed markings and wear patters, esp. on the Z-notches that would indicate poor point-to-point contact between adjacent blades. Type 1-3 blades were designed to be parallel in the cold setting, whereas the new Type 5 design is designed with a taper such that it goes parallel in the operating condition.

Blade Configuration (e.g. Hard-Facing on Z-Notches)

Period 4...

Period 3...

Maybe discussion on the history of the different types of blades.

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Bartow L-0 RCA Draft Working Meeting

08/24/2017

Excessive Steam Flow

- For Periods 1-5, and by a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the avoidance zone hours relative to total operating hours.
- Damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine. All turbine end L-0 blades were replaced. Some degree of fretting was observed on the contact surfaces of both turbine and generator ends of the machine.
- For Period 3, additional damage seen on the shroud Z-Lock contact surfaces relative to other Periods, was likely due to loss of dampening at the snubber, which were HVOF coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

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Empirical Support for Root Cause					
Period	Operating Hours	Excessive Steam Flow			
		Driving Mechanism Present	Avoidance Zone Exceedance Hours	hrs./(1k Op hrs.)	Normalized Ranking
1	21734	X	2466	0.11	1.00
2	21284		1	0.00	0.00
3	10286	X	240	0.02	0.21
4	2942		1.15	0.00	0.00
5	1561		0	0.00	0.00

- Column D – Captured operating hours above 15,000 lb/ft²-hr limit as indicated by the IP Exh pressure
- Column E – No. of operating hours above the limit divided by the period operating hours
- Column F – Normalized against the highest value.

Pressure Pulses

- Hood spray operation – from commissioning – was not programmed to the OEM specifications. Specifically, the hood sprays come on with the curtain sprays, and this is counter to the MHI design, which only specifies that sprays come on during start-up, shut-down and high temperatures in the exhaust.
- Over time, hood spray pressure decayed due to apparent valve trim contamination and upstream filter screen debris.

CONFIDENTIAL**Bartow 4S Root Cause Analysis – Evaluation of Contributing Factors**

- LP Turbine Back-End Loading (>15,000 lb./hr./ft.²)
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Blade Configuration (e.g. Hard-Facing on Z-Notches)

Period 4...

Period 3...

Maybe discussion on the history of the different types of blades.

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- Information provided by the hood spray nozzle vendor suggest that low pressures lead to poor atomization. It is further speculated that larger droplet size can lead to pressure pulses as water droplet vaporize in the exhaust flow.

Empirical Support for Root Cause						
Pressure Pulses						
Period	Operating Hours	Driving Mechanism Present	Avg. Hood Spray Pressure (psig)	Hours of Hood Spray Operation	% of Total Operating Hours	Normalized Ranking
1	21734		35.2	5098.4	23	0.68
2	21284	X	13.2	7342.7	34	1.00
3	10286	X	10.4	439.7	4	0.12
4	2942		5.5	173.8	6	0.17
5	1561	X	8.7	93.1	6	0.17

- Hours of hood spray operation are weighted – 1.00 multiplier for 50psig linearly varying to 1.75 at 5psig.
- % of Total Op Hrs is the weighted hours divided by total operating hours.
- Normalized against maximum %

Thermal Distress at L-O Exit (dTsh/dt)

- Calculated a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values over 20 degrees F when a CT is being blended off or on the steam turbine and the steam turbine output is greater than 50 MW.
- The limits of 20 degrees F and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system.
- This process of determining blends that were outside of the condenser OEM's recommended operating practices for the spargers.

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		Support for Root Cause			
		Thermal Distress (dTsh/dt)			
Period	Operating Hours	Driving Mechanism Present	Counts (> 20Fsh/min)	Counts/(1k Op hrs.)	Normalized Ranking
1	21734	X	13	0.60	0.17
2	21284	X	7	0.33	0.09
3	10286	X	97	3.60	1.00
4	2942	X	3	1.02	0.28
5	1561	X	5	3.20	0.89

- Counts are defined as blends where there was a rate of change in superheat temperature greater than 20 degrees at the hood spray thermocouples.
- Continue speaking to the columns definitions...

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CONFIDENTIAL**Loss of Dampening**

- For Period 3, additional damage seen on the shroud Z-Lock contact surfaces relative to other Periods, was likely due to loss of dampening at the snubber, which were HVOF coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

Blade Fitment (Contact Surfaces)

-

Other Mechanisms

- Operation in higher dynamic stimulus zones within the normal operating window – i.e. outside the avoidance zone – as identified by strain gauge testing in December 2014.
- List others here...

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Empirical Support for Root Cause

- Period 1 Jun 2009 to Mar 2012
- Period 2 Apr 2012 to Aug 2014
- Period 3 Dec 2014 to Apr 2016
- Period 4 May 2016 to Oct 2016
- Period 5 Dec 2016 to Feb 2017

Excessive Steam Flow - Notes

- "Avoidance Zone Exceedance Hours" - Measured number of operating hours in exceedance of 15,000 lb/hr-ft² limit as indicated by the IP exhaust pressure
- "Exceedance Hours / (1k Operating Hours)" - Number of exceedance hours per 1000 hours of operation in a given period
- "Normalized Ranking" - Data normalized against the highest value in the column, "Exceedance Hours / (1k Operating Hours)"

Period	Excessive Steam Flow			
	Operating Hours	Potential Factor Present	Avoidance Zone Exceedance Hours	Exceedance Hours / (1k Operating Hours)
1	21,794	X	2,466	0.11
2	21,284		1	0.00
3	10,286	X	240	0.02
4	2,942		1	0.00
5	1,561		0	0.00

Thermal Distress (dT_{max}/dt) Notes

- "Counts (DT > 20 deg. FSH / Minute)" - "Counts" are defined as the number of measurable blends where there was a slope change (+/-) greater than (20 degrees superheat / min) at the hood spray thermocouples - Data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW
- "Counts / (1k Operating Hours)" - Number of "Counts" per 1000 hours of operation in a given period
- "Normalized Ranking" - Data normalized against the highest value in the column, "Counts / (1k Operating Hours)"

Period	Thermal Distress (dT _{max} /dt)		
	Operating Hours	Potential Factor Present	Counts (DT > 20 deg. FSH / Minute)
1	21,794	X	13
2	21,284	X	7
3	10,286	X	37
4	2,942	X	3
5	1,561	X	5

Pressure Pulses - Notes

- "Avg. Hood Spray Pressure (psig)" - Calculated from P1 historian data
- "Hours of Hood Spray Operation" - "Hours of Hood Spray Operation" is a weighted value - There is a 1.00 multiplier at 50 psig varying linearly to a 1.75 multiplier at 5 psig
- "% of Total Operating Hours" - The "weighted" hours of hood spray operation divided by the total number of operating hours - converted to a percentage value
- "Normalized Ranking" - Data normalized against the highest percentage value in the column, "% of Total Operating Hours"

Period	Pressure Pulses			
	Operating Hours	Potential Factor Present	Avg. Hood Spray Pressure (psig)	Hours of Hood Spray Operation
1	21,794	X	35.2	5,098
2	21,284	X	13.2	7,343
3	10,286	X	10.4	440
4	2,942	X	5.5	174
5	1,561	X	8.7	93

Period	Loss of Dampening	
	Operating Hours	Potential Factor Present
1	21,794	N/A
2	21,284	N/A
3	10,286	N/A
4	2,942	X
5	1,561	N/A

Period	Blade Fitment	
	Operating Hours	Potential Factor Present
1	21,794	X
2	21,284	X

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Blade Fitment - Notes

- "Blade Fitment" - References the gap measurements for both the mid-span mubbbers and the shroud Z-Lock contact surfaces

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3	10,286	X	1.00
4	2,942	X	1.00
5	1,561	X	5.00

	Damage Assessment				
	Period 1	Period 2	Period 3	Period 4	Period 5
Operating Hours	21,734	21,284	10,286	2,942	1,561
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE	0 TE / 8 GE
Comments	Not Captured	TE and GE Mid-Span Snubbers Found Intact. Minimal TE and GE Shroud Chipping Observed.	High Degree of Wear Observed on Z-Locks. Z-Lock Damage / Loss of Material on TE Blade No. 43 Rendered It "Freestanding"	One (1) TE L-O Found with Tip Liberation at Airfoil of Trailing Edge	High Degree of Wear Observed on Z-Locks.

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Executive Summary

Duke and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 12 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation. During a presentation given at Bartow Station on 15 March 2017, MHPS suggested the sole root cause for Period 3 (Dec 2014–Mar 2016) was "operation in the avoidance zone". While Duke Engineering would agree that operation in the "avoidance zone" is certainly a *contributing factor* to the shroud chipping experienced in Period 3, it is not the only driving mechanism that should be considered when trying to determine root cause for the Period 3 Bartow Unit 4S event, or any of the previous/subsequent events for that matter.

After months of study, Duke Engineering believes the following to be the most significant contributing factors toward root cause of the history of Bartow-Unit 4S L-0 events.

- Low Pressure (LP) Turbine Excessive Steam Flow
- Thermal Distress at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operations
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Loss of Dampening (e.g. Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces)

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above.

Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

Commented [PVCL]: For period 3 only.

Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

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Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data analysis – learned (and made it known to Duke) that a significant contributing factor toward root cause of the L-O blade failures was extremely high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40” L-O fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40” L-O fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an “avoidance zone” chart with instructions from MHPS not to run to the right side of the curve – the lone exception being “brief” operation during transient conditions.

While Duke Engineering agrees that back-end loading should be considered a significant contributing factor toward root cause, one cannot definitively conclude that it has been the root cause of all five (5) of the documented L-O events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the “avoidance zone” of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

[REDACTED]

[REDACTED]

While the amount of Z-Lock wear is not quantified for Period 1 and 3, photographic evidence suggests that the amount of wear is similar. It is therefore difficult to conclude that damage to the L-O blades in Period 3 is solely due to unit operation above the exhaust flow limit.

With the L-Os currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern.

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Commented [PVC3]: However, MHPS has not done any review and released us to go to higher LP inlet pressures/flows.

Blending Operations – Thermal Distress (dT_{TH}/dt) at LP Turbine Exhaust

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact the L-O blades. Since the design of the condenser includes spargers, or “dump tubes”, for the hot reheat (HRH) and LP bypass steam flows from each of the four

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combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM.

[REDACTED]

While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify times to look at additional blend parameters.

Below is a quick comparison of the number "counts" that meet the criteria for Periods 1-5.

		Number of Blends (or "Counts") Meeting Criteria
Period 1		1
Period 2		7
Period 3		31**
Period 4		3
Period 5		5

*Includes the time period during commissioning from 1/1/2009 to 6/1/2009
 **Excludes 6 blends that meet criteria during strain gauge testing in December 2014

Commented [JCE4]: Paul, I changed the middle column to hours (from day) to stay consistent with other charts we've created. The hours I have for Period 1 (21,734) - do they include the time frame you've included next to the first *, or are they Period 1 operating hours post-COD?

Pressure Pulses During Hood/Curtain Spray Operation(s)

The RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

Review of MHPS-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW

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- Hood spray thermocouple reading greater than 160 degrees F

During review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or trip when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrument issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the valve had filled with debris in prior years.

The chart below demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

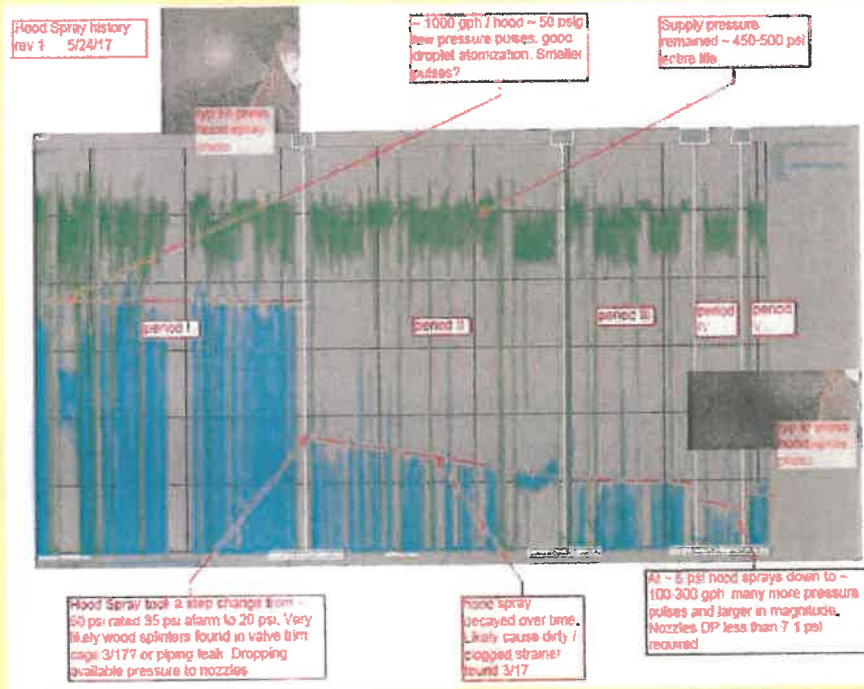
Commented [JCE5]: Which valve is this -- The control valve mentioned in the above paragraph?

Commented [JCE6]: Same comment as JCE4.

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Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

(insert text)

Loss of Dampening (e.g. Hard-Facing on Mid-span Snubbers and Z-Lock Contact Surfaces)

(insert text)

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Appendix A: Bartow L-0 Event Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	450 MW (420 Nameplate)	420 MW per MHI	450 MW	450 MW	390 MW
Operating Restrictions	None	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exceedance	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,320 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 3,000 hrs)	0 hrs
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *z-lock and airfoils	0 TE / 8 GE
Worn Z-locks	not captured		high degree of wear observed		high degree of wear observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) & continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).	Not a forced outage. Outage planned to upgrade to "heavy duty" blades. Some blade damage was observed from removed service blades. Blade telemetry instrumentation installed (Dec 21 - Dec 24, 2014)	Blade telemetry testing; Intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed. Blade telemetry data also shows higher stress areas in operation outside the avoidance zone based on blade strain data (no operating limitations placed around these areas by MHPS), data indicates we operated in these zones "X hrs during the period.	Blade loss of material, crack initiation in high stress area of airfoil. Stallite hard facing had been added to the blade z-lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection. At first, MHPS did not support this recommendation, nor did they support the idea that "loss of mass" had occurred.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events. Jan 2017 "loss of mass" event - blade fragment projectile traveled through the LP turbine rupture disk diaphragm. Dental mold impression of failure surfaces indicate ~10 ⁶ 7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail rubber). Confirmation from the Harris met lab evaluation should help determine cracking mechanism
Information shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested. MHPS learned through Duke Engineering (intentional) that we were investigating blending and its impact to the Condenser/ST. MHPS RCA team for the first time learned what "blending in" and "blending out" meant

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Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	Height same as Bartow
Z-Lock	No HVOF	No HVOF	HVOF applied	No HVOF
Blade design	Orig.	Orig.	Orig.	Attack Angle change
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	In commissioning (~1yr)
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

Deleted: New

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Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0 blade failures is that the OEM designed blades were inadequate for the operating conditions with which they were subjected.

Duke Engineering believes the root cause for Periods 1-5 involves more than driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.². Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. Today, there is agreement between both parties that there is not just one simple root cause.

After months of study, Duke Engineering believes the following to be the most significant contributing factors toward root cause of the history of Bartow Unit 4S L-0 events.

- Low Pressure (LP) Turbine Excessive Steam Flow
- Thermal Distress at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operations
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening (e.g. Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces)
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the telemetry test conducted during December 2014 – blade response data that is then extrapolated to theorize potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution (e.g. redesigned blades) for the Bartow LP section and subsequent field measurements taken following various operating configurations/scenarios that are integral to unrestricted 4 x 1 combined cycle operation will be necessary to confirm the contributing factor postulations. In other words, the correctness of the Duke and/or MHPS root cause position(s) can only be confirmed with the successful field operation of the unit.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above.

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Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

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Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data analysis – learned (and made it known to Duke) that a significant contributing factor toward root cause of the L-0 blade failures was extremely high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

While Duke Engineering agrees that back-end loading should be considered a significant contributing factor toward root cause, one cannot definitively conclude that it has been the root cause of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours – 2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

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Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1 – a factor of 10 fewer hours for Period 3 – there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Period 1 and 3, photographic evidence suggests that the amount of wear is similar. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

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With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern.

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Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact the L-0 blades. Since the design of the condenser includes spargers, or "dump tubes", for the hot reheat (HRH) and LP bypass steam flows from each of the four combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI DataLink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or "counts". "Counts" are defined as the number of measureable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Below is a quick comparison of the number "counts" that meet the criteria for Periods 1-5.

	Number of Operating Hours in Each Period	Number of Blends (or "Counts") Meeting Criteria
Period 1		13
Period 2		7
Period 3		31**
Period 4		3
Period 5		5

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*Includes the time period during commissioning from 1/1/2009 to 6/1/2009

**Excludes 6 blends that meet criteria during strain gauge testing in December 2014

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the valve had filled with debris in prior years' operating.

The chart below demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

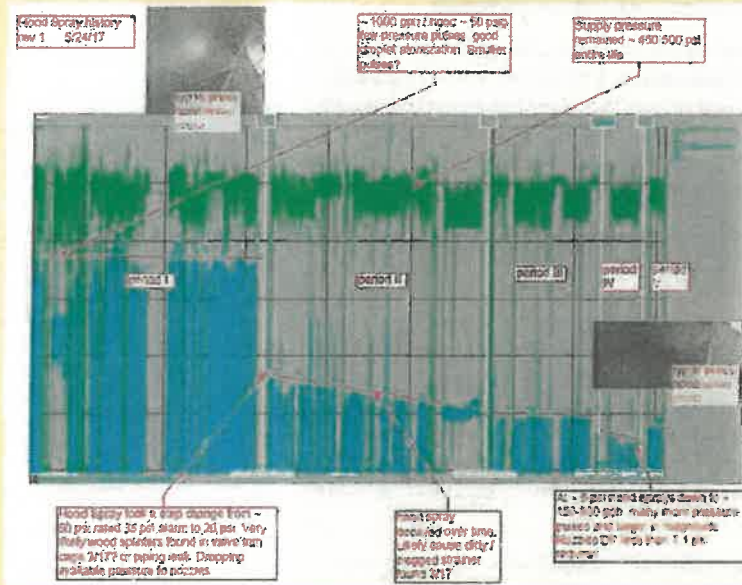
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Commented [JCE5]: Which valve is this – The control valve mentioned in the above paragraph?

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Zone Analysis – Shroud Fretting Fatigue

(insert text)

Loss of Dampening (e.g. Hard-Facing on Mid-span Snubbers and Z-Lock Contact Surfaces)

The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers, which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting locating became the blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward root cause will continue in the next section that speaks to blade fitment.

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Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the root cause investigation between Periods 3 and 4, technical questions arose relative to “as left” blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren’t both taken into consideration together, then as the blades began to “untwist” as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture “worst case” geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a Type 5 blade redesign. Planned design changes intend to reduce blade response and induced dynamic stress that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

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Appendix A: Bartow L-0 Event Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	450 MW (420 Nameplate)	420 MW per MHI	450 MW	450 MW	390 MW
Operating Restrictions	None	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exposure	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,920 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 9,000 hrs)	0 hrs
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *z-lock and airfoils	0 TE / 8 GE
Worn Z-locks	not captured		high degree of wear observed		high degree of wear observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 8x1 heat balance) & continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).	Not a forced outage. Outage planned to upgrade to "heavy duty" blades. Some blade damage was observed from removed service blades. Blade telemetry instrumentation installed (Dec 21 - Dec 24, 2014)	Blade telemetry testing: Intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed. Blade telemetry data also shows higher stress areas in operation outside the avoidance zone based on blade strain data (no operating limitations placed around these areas by MHPS), data indicates we operated in these zones ~X hrs during the period.	Blade loss of material, crack initiation in high stress area of airfoil. Sealine hard facing had been added to the blade z-lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection. At first, MHPS did not support this recommendation, nor did they support the idea that "loss of mass" had occurred.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events. Jan 2017 "loss of mass" event - blade fragment projectile traveled through the LP turbine rupture disk diaphragm. Dental mold impression of failure surfaces indicate ~10 ⁶ 7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber). Confirmation from the Harris met lab evaluation should help determine cracking mechanism
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Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	Height same as Bartow
Z-Lock	No HVOF	No HVOF	HVOF applied	No HVOF
Blade design	Orig.	Orig.	Orig.	Attack Angle change
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	In commissioning (~1yr)
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

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Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0blade failures is that the OEM designed blades were inadequate for the operating conditions with which they were subjected.

Duke Engineering believes the root cause for Periods 1-5 involves more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.². Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. Today, there is agreement between both parties that there is not just one simple root cause.

After months of study, Duke Engineering believes the following to be the most significant contributing factors toward root cause of the history of Bartow Unit 4S L-0 events.

- Low Pressure (LP) Turbine Excessive Steam Flow
- Thermal Distress at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operations
- **Zone Analysis – Shroud Fretting Fatigue**
- Loss of Dampening (e.g. Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces)
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the telemetry test conducted during December 2014 – blade response data that is then extrapolated to theorize potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution (e.g. redesigned blades) for the Bartow LP section and subsequent field measurements taken following various operating configurations/scenarios that are integral to unrestricted 4 x 1 combined cycle operation will be necessary to confirm the contributing factor postulations. In other words, the correctness of the Duke and/or MHPS root cause position(s) can only be confirmed with the successful field operation of the unit.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above.

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Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

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Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

Commented [PVC1]: For period 3 only

Since commissioning there have been five (5) events triggered by L-O blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-O blade in efforts to address the failures (see Appendix B for L-O modifications). To date, the modifications have not resulted in improved reliability or performance of the L-O blades in service at Bartow. The number of blade failures and problems with ST L-O blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-O fleet. The most common reported issue from the MHPS 40" L-O blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-O rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data analysis – learned (and made it known to Duke) that a significant contributing factor toward root cause of the L-O blade failures was extremely high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-O fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40" L-O fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

While Duke Engineering agrees that back-end loading should be considered a significant contributing factor toward root cause, one cannot definitively conclude that it has been the root cause of all five (5) of the documented L-O events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours – 2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

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Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1 – a factor of 10 fewer hours for Period 3 – there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Period 1 and 3, photographic evidence suggests that the amount of wear is similar. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern.

Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact the L-0 blades. Since the design of the condenser includes spargers, or "dump tubes", for the hot reheat (HRH) and LP bypass steam flows from each of the four combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or "counts". "Counts" are defined as the number of measureable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Below is a quick comparison of the number "counts" that meet the criteria for Periods 1-5.

	Number of Blends (or "Counts") Meeting Criteria
Period 1	13
Period 2	7
Period 3	3 ^{**}
Period 4	3
Period 5	5

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Commented [PVC3]: However, MHPS has not done any review and released us to go to higher LP inlet pressures/flows.

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*includes the time period during commissioning from 1/1/2009 to 6/1/2009

**includes blends that meet the criteria during strain gauge testing in December 2014

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the valve had filled with debris in prior years' operating.

The chart below demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

Commented [JCBA]: Paul, I changed the middle column to hours (from day) to stay consistent with other charts we've created. The hours I have for Period 1 (21,734) – do they include the time frame you've included next to the first *, or are they Period 1 operating hours post-COD?

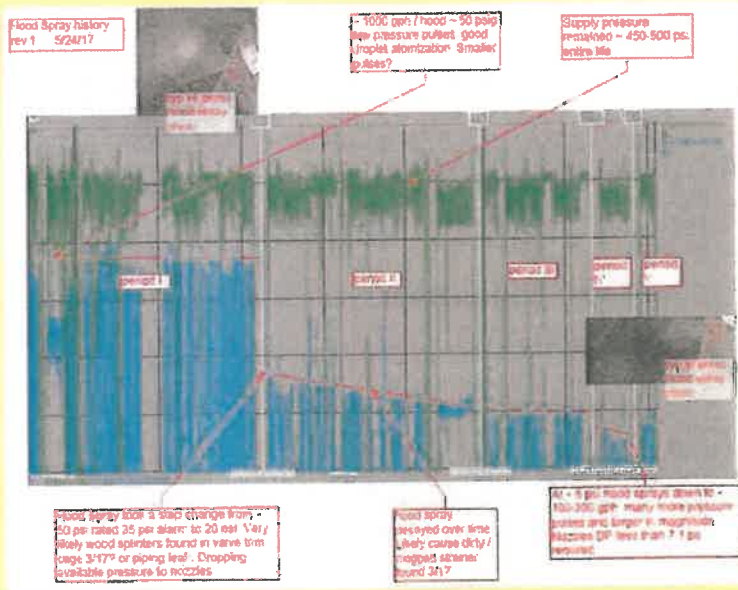
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Commented [JCBS]: Which valve is this – The control valve mentioned in the above paragraph? Yes.

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Zone Analysis -- Shroud Fretting, Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, MHPs identified areas (referred to as zones) where blade response was high, but still below their design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1 thru Zone F3 (shown by the red rectangles in the figure below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period.

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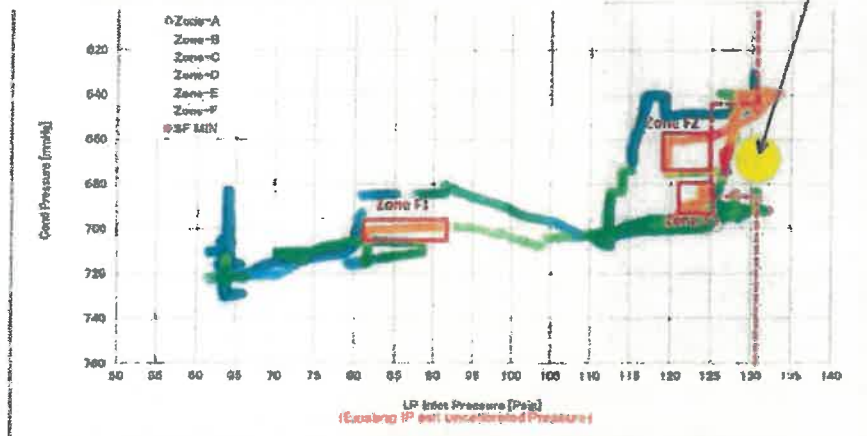
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Damage Mechanism

Blade Response – Design Margin
 Example : Shroud Fretting Fatigue

Unable to test due to excessive blade response



- Blade response is evaluated through the integration of the stress response all the modes between 180Hz to 120Hz

Figure X: Data presented by MHPS from a presentation dated YY/YY/YYYY

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Table Y shows the breakdown of time in hours in each of the three defined F zones for each period. The total time in the 3 zones is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

	Time In Zone				Total Turbine Operating Hours	% Time In Zone F
	F1	F2	F3	Total		
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

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Table Y: Time in hours spent in each Zone and the total compared with operating time

The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in

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Figure XX. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.



Figure XX: Photo of Z-notch from Period 5 showing wear of contact surface

Period 5 did have its share of higher energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending. The total of 20 hours of blend time does not appear to justify the wear seen.

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Loss of Dampening (e.g. Hard-Facing on Mid-span Snubbers and Z-Lock Contact Surfaces)

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The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers, which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting locating became the blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-O blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward root cause will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

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The long-term solution (e.g. redesigned blades) for the Bartow LP section and subsequent field measurements taken following various operating configurations/scenarios that are integral to unrestricted 4 x 1 combined cycle operation will be necessary to confirm the contributing factor postulations. In other words, the correctness of the Duke and/or MHPS root cause position(s) can only be confirmed with the successful field operation of the unit.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above.

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Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0 blade failures is that the OEM designed last stage blades had little or no design margins for the actual operating conditions that exist for the overall Bartow Combine Cycle Unit.

Duke Engineering believes the root cause for Periods 1-5 involves more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.². Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. Today, there is agreement between both parties that there is not just one simple root cause.

After months of study, Duke Engineering believes the following to be the most significant contributing factors toward root cause of the history of Bartow Unit 4S L-0 events.

- Low Pressure (LP) Turbine Excessive Steam Flow
- Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
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Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration.

Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data analysis – learned (and made it known to Duke) that a significant contributing factor toward root cause of the L-0 blade failures was extremely high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

While Duke Engineering agrees that back-end loading should be considered a significant contributing factor toward root cause, one cannot definitively conclude that it has been the root cause of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

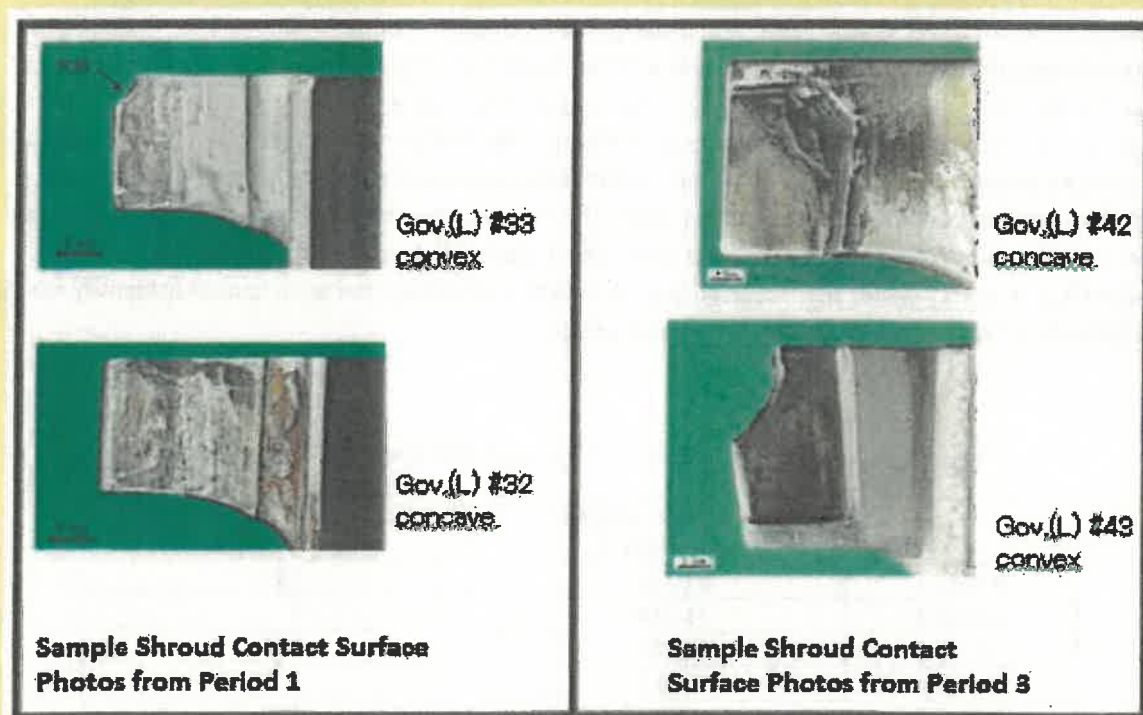
By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours – 2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

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Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1 – a factor of 10 fewer hours for Period 3 – there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Periods 1 and 3, photographic evidence suggests that the amount of wear is much greater for Period 3, as shown below in Figure 1. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

Figure 1 – Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern at the current LP inlet operating limits. MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current LP inlet operating limits due to concerns for impacts to upstream blading – i.e. the L-1 blade sets.

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CONFIDENTIAL**Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust**

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact the L-0 blades. Since the design of the condenser includes spargers, or “dump tubes”, for the hot reheat (HRH) and LP bypass steam flows from each of the four combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or “counts”. “Counts” are defined as the number of measureable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Table 1 -- Quick Comparison of the Number of “Counts” that Meet the Criteria for Periods 1-5.

	Number of Operating Hours in Each Period	Number of Blends (or “Counts”) Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

*Includes 6 blends that meet the criteria during strain gauge testing in December 2014

DECLASSIFIED**Pressure Pulses During Hood/Curtain Spray Operation(s)**

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

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A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

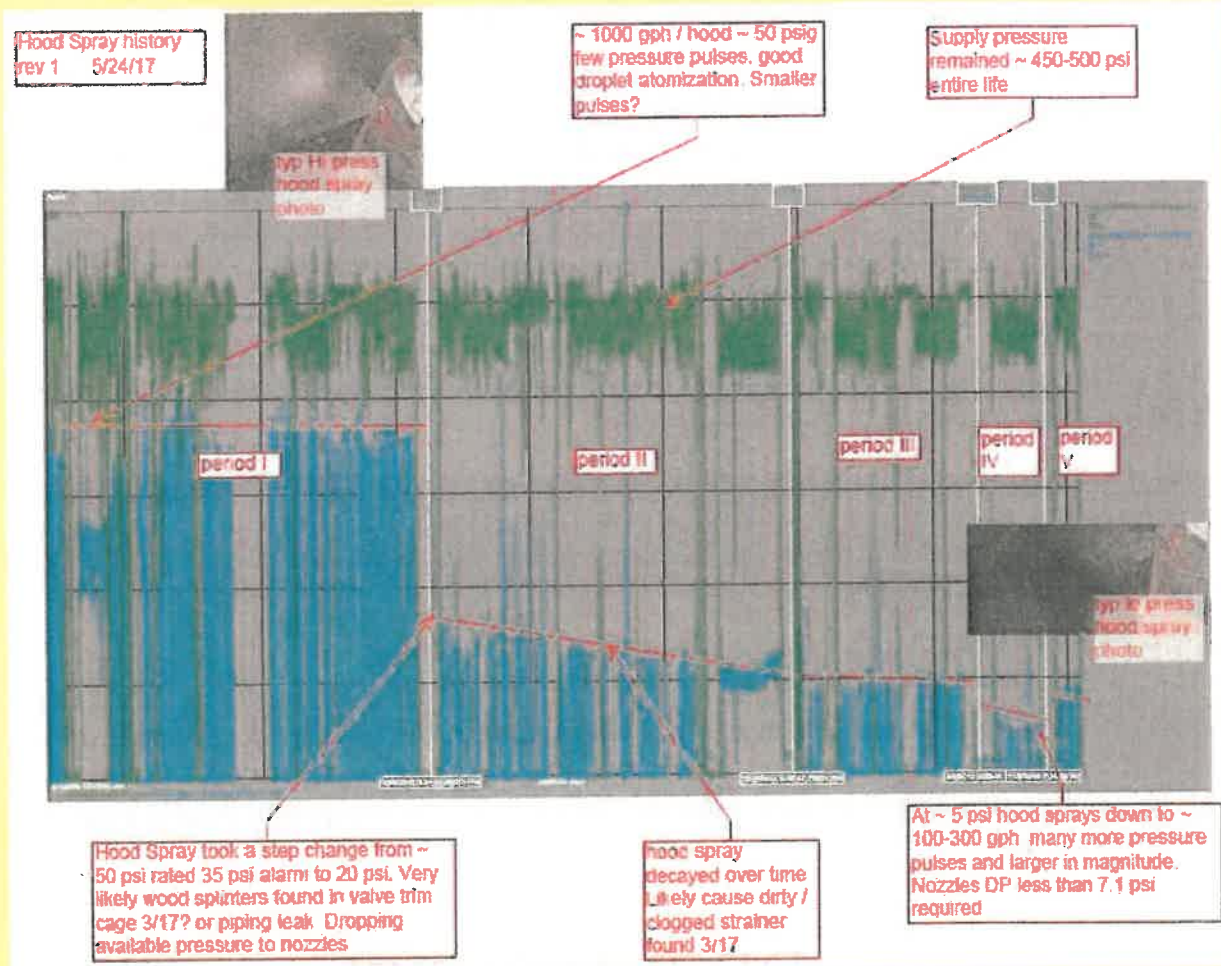
Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the hood sprays control valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the same control valve had filled with debris in prior years' operating.

Figure 2, below, demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

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Figure 2 -- Hood Spray Pressure Degradation Over Periods 1-5



Zone Analysis – Shroud Fretting Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, MHPS identified areas (referred to as “Zones”) where blade response was high, but still below the OEM design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1 through Zone F3 (shown by the red rectangles in Figure 3, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period.

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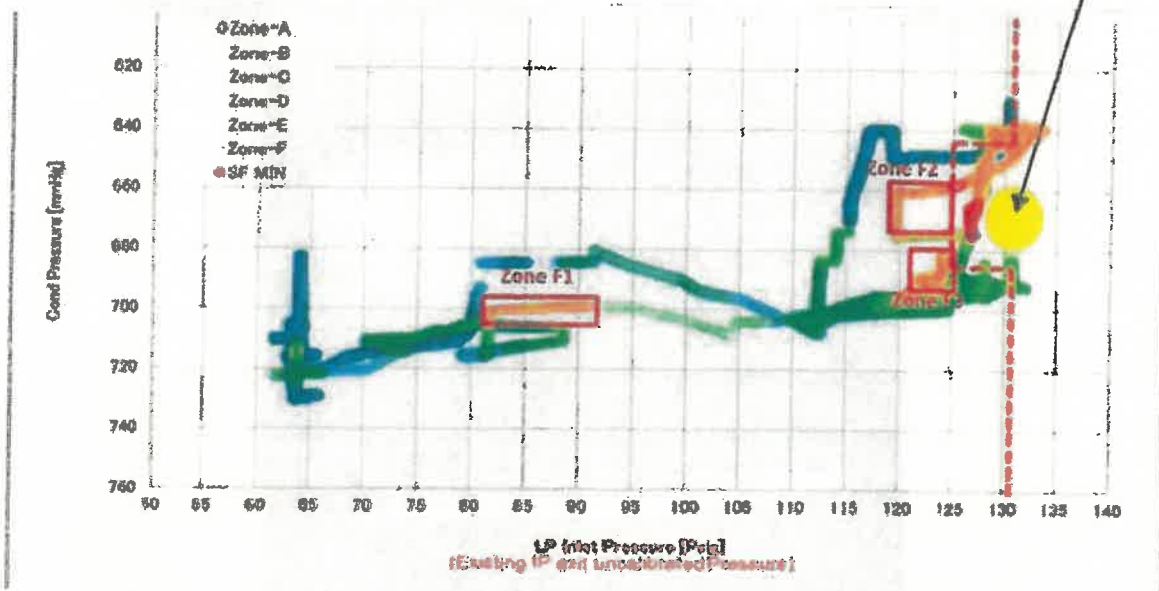
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Figure 3 – Data Presented by MHPS During a Presentation Dated 15 March 2017

Damage Mechanism

Blade Response – Design Margin
Example : Shroud Fretting Fatigue

Unable to test due to excessive blade response



- Blade response is evaluated through the integration of the stress response all the modes between 180Hz to 120Hz

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

Table 2 -- Time (in Hours) Spent in Each Zone and the Total Compared with Operating Time

	Time In Zone				Total Turbine Operating Hours	% Time in Zone F
	F1	F2	F3	Total		
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

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The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure 4. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

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Figure 4 – Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear



Period 5 did have its share of higher energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending. The total of 20 hours of blend time does not appear to justify the wear seen.

Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers, which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting location became the blade

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itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward root cause will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the root cause investigation between Periods 3 and 4, technical questions arose relative to “as left” blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren’t both taken into consideration together, then as the blades began to “untwist” as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture “worst case” geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

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Appendix A - Bartow L-0 Event Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW (Nameplate)	420 MW	450 MW	450 MW	390 MW
Operating Restrictions	None - MHPS Intent Was to Follow Heat Balance Diagrams.	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111 psig Limit on IP Exhaust
Blade Overspeed Condition	Overspeed Testing in MFG		Overspeed Tested in Japan	No Overspeed Testing	No Overspeed Testing
Avoidance Zone Exceedance	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,284 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period events	<p>MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) and to continue the warranty.</p> <p>MHPSA was storing for Tenaska (purchased grey market, stored by OEM).</p> <p>ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).</p>	<p>Not a forced outage. Outage planned to upgrade to "heavy duty" blades.</p> <p>Some blade damage (e.g. chipping at contact corners) was observed from removed service blades.</p> <p>Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.</p>	<p>During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits - unit ran in zone for <20 hrs.</p> <p>No blade cracking observed after testing (when the test instrumentation removed).</p>	<p>Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil.</p> <p>Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure.</p> <p>Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.</p>	<p>Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events.</p> <p>Jan 2017 "loss of mass" event - blade fragment projectile traveled through the LP turbine rupture disk diaphragm.</p> <p>Dental mold impression of failure surfaces indicate ~10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).</p>
Information Shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.

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Appendix B - MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	<i>Different Radial Height Relative to Bartow L-0 (About 1")</i>
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	No HVOF
Blade design	Orig.	Orig.	Orig.	<i>Attack Angle Change</i>
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	<i>In commissioning (~1yr)</i>
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

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Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Commented [PVC1]: For period 3 only.

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Blending Operations – Thermal Distress (dT_{RH}/dt) at LP Turbine Exhaust

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact the L-0 blades. Since the design of the condenser includes spargers, or "dump tubes", for the hot reheat (HRH) and LP bypass steam flows from each of the four combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or "counts". "Counts" are defined as the number of measureable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

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Commented [PVC3]: However, MHPS has not done any review and released us to go to higher LP inlet pressures/flows.

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Table 1 -- Quick Comparison of the Number of "Counts" that Meet the Criteria for Periods 1-5.

	Number of Operating Hours	Number of Blends (or "Counts") Meeting Criteria
Period 1		13
Period 2		7
Period 3		37**
Period 4		3
Period 5		5

*Includes the time period during commissioning from 1/1/2009 to 6/1/2009

**Includes 6 blends that meet the criteria during strain gauge testing in December 2014

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Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place -- similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the valve had filled with debris in prior years' operating.

Commented [JCES]: Which valve is this -- The control valve mentioned in the above paragraph?

Figure 1, below, demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was

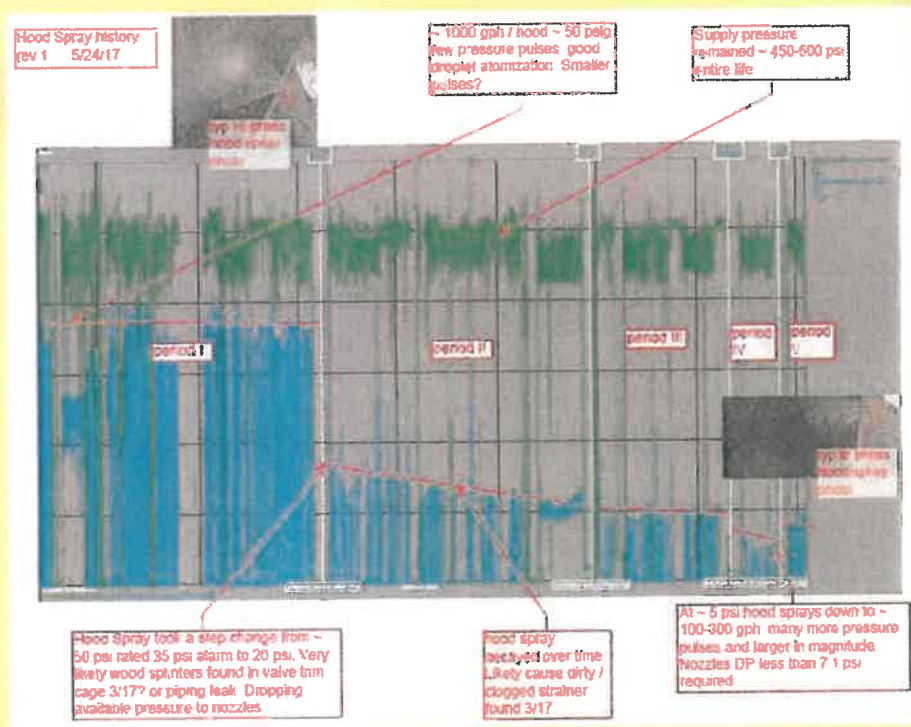
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verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

Figure 1 – Hood Spray Pressure Degradation Over Periods 1-5



Zone Analysis – Shroud Fretting Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, MHPs identified areas (referred to as "Zones") where blade response was high, but still below the OEM design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1 through Zone F3 (shown by the red rectangles in Figure 2, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period.

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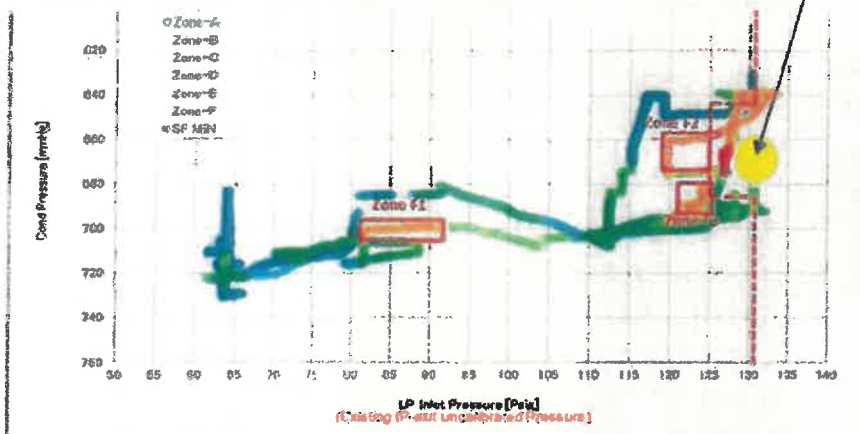
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Figure 2 – Data Presented by MHP5 During a Presentation Dated 15 March 2017

Damage Mechanism

Blade Response – Design Margin
 Example : Shroud Fretting Fatigue

Unable to test due to excessive blade response



- Blade response is evaluated through the integration of the stress response all the modes between 160Hz to 120Hz

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

Table 2 – Time (in Hours) Spent in Each Zone and the Total Compared with Operating Time

	Time In Zone				Total Turbine Operating Hours	% Time In Zone F
	F1	F2	F3	Total		
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

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The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure XX. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

Figure 3 – Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear



Period 5 did have its share of higher energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending. The total of 20 hours of blend time does not appear to justify the wear seen.

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Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers, which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting locating became the blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-O blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward root cause will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the root cause investigation between Periods 3 and 4, technical questions arose relative to “as left” blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren’t both taken into consideration together, then as the blades began to “untwist” as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-O blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture “worst case” geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

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Appendix A: Bartow L-0 Event Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW Nameplate	420 MW Nameplate	450 MW	450 MW	390 MW
Operating Restrictions	None - MHPS intent was to follow best balance	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exceedance	2,466 hrs. (of 11,145 hrs.)	1 hr (of 11,145 hrs)	240 hrs (of 11,145 hrs)	1.15 hrs (of 11,145 hrs)	0 hrs (of 11,145 hrs)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-locks	0 TE / 0 GE	0 TE / 0 GE	84 TE / 5 GE - mostly corner chipping, 1 z-notch with close to half	1 TE / 2 GE *z-lock and airfoils	0 TE / 8 GE
Worn Z-locks	Moderate amount of surface fretting and pitting observed	Moderate amount of surface fretting and pitting observed	high degree of wear observed	Evidence of poor contact alignment seen.	high degree of wear hours run observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) & continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).	Not a forced outage. Outage planned to upgrade to "heavy duty" blades. Some minor blade damage (chips at contact corners) was observed from removed service blades. Blade telemetry instrumentation installed ("Dec 21 - Dec 24", 2014)	Blade telemetry testing; intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed.	Blade loss of material, crack initiation in high stress area of airfoil. Stellite hard facing had been added to the blade z-lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events. Jan 2017 "loss of mass" event -- blade fragment projectile traveled through the LP turbine rupture disk diaphragm. Dental mold impression of failure surfaces indicate "10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber)."
Information shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.

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Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	Different radial height (about 1 in)
Z-Lock	No HVOF	No HVOF	45° corner, HVOF applied	No HVOF
Blade design	Orig.	Orig.	Orig.	Attack Angle change
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	In commissioning (~1yr)
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

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February 6, 2018

Executive Summary

Over the past 3 plus years, Duke Energy Florida LLC (Duke), at times working independently and at times together with Mitsubishi Hitachi Power Systems (MHPS), undertook a root cause analysis (RCA) of the cause(s) for the Unit 4S L-0 blade cracks and failures that occurred during normal station operations at Bartow Station. The intervals between failures had become shorter after each failure despite MHPS's attempts to improve the blades' performance and the station's adherence to the revised OEM operating instructions received after each successive failure.

Only after the telemetry test was completed and after the onset of Period 3, in approximately March 2015, (as a result of the telemetry test) did MHPS create an "avoidance zone" in which the station was not to operate except as needed to ramp up or down. Bartow operated in the avoidance zone only 1.15 hours in Period 4 and 0 hours in Period 5, but suffered two (2) further failures in successively shorter periods. Thus, after the fifth failure, Duke concluded that operation in MHPS' designated avoidance zone did not explain the failures and looked at whether other factors potentially were related or contributed to the failures.

Duke considered both operational and design aspects. With respect to operational factors, the Duke team used the Plant Information ("PI") data historian and operational data from each period and retroactively calculated¹ whether those factors had any correlation to the failures. Potential factors in the operational category included:

- Operations in MHPS Avoidance Zone -- Low Pressure (LP) Turbine "Excessive" Steam Flow
- Bartow Blending Operations – Potential Thermal Distress (Rate of Change in Super Heat Over Time, dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)

Duke Engineering concluded that there was no correlation between any one of the above-listed factors and the five (5) failure periods. Notably, Duke was only able to study each factor independently based on available data. In the absence of (1) blade telemetry, (2) duplication of the factors in various combinations, and (3) operation in varying but normal conditions, it is not possible to study how each factor relates to and interacts with any other factor, if at all.

Duke also studied design factors unique to MHPS 40" steel blades. This aspect of the RCA was largely deductive because MHPS controls design data, although MHPS did provide FEA stress and frequency analyses, material properties, and some dimensional information. The following factors were included in this portion of the study:

- Zone Analysis – Shroud Fretting Fatigue

¹ Because MHPS's operational constraint called the Avoidance Zone was not provided by MHPS until after the onset of Period 3, one could only look at hours in that zone after-the-fact for Periods 1 and 2.

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October 11, 2017

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Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-O blades to crack and break during operation.

Duke's position is as follows: The Bartow steam turbine (ST) 40" L-O blade failures are being driven by a non-synchronous self-excited vibration (flutter) of the L-O blades during operation. In our and MHPS's evaluation of the root cause neither party has been successful in conclusively identifying the factor(s) that are causing the failures. There are a series of contributing factors that have been identified but the correlation and predictability of these contributing factors and the magnitude of their interactions has been difficult if not impossible to predict without having conducted further instrumented testing of the L-O blades in operation. Any conclusions derived from our efforts and discussed in this document are based on our best ability to correlate data with events in operation and findings with L-O blade inspections/failures. that the OEM designed last stage blades had little or no design margins for the actual operating conditions that exist for the overall Bartow Combine Cycle Unit.

Commented [MB1]: This is important to be stated but needs to find a different place in the document. It should also be stated that there is no industry experience with a 4x1 configuration like Bartow...which leads to MHPS not fully understanding the operating conditions, thus having a L-O blade that we are now determining un-fit for operation with not enough design margin for this station configuration.

Duke Engineering believes the root cause for Periods 1-5 involves more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.². Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. MHPS has since changed its position and today there is agreement between both parties that there is not just one simple root cause.

After months of study (and with input from MHPS) Duke Engineering believes the following to be the most significant contributing factors toward root cause of the history of Bartow Unit 4S L-O events:

- Low Pressure (LP) Turbine Excessive Steam Flow
- Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the telemetry test conducted during December 2014 – blade response data that is then extrapolated to develop potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution for the Bartow LP section is to replace the L-O blades or retrofit of the LP steam path with a more capable/reliable design. With either scenario, blade telemetry instrumentation and blade vibration

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monitoring will be necessary to conclusively determine and eliminate the magnitude and impact of the identified contributing factors.

This technical paper will speak briefly of the history of L-O blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above.

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Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration.

Since commissioning there have been five (5) events triggered by L-O blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-O blade in efforts to address the failures (see Appendix B for L-O modifications). To date, the modifications have not resulted in improved reliability or performance of the L-O blades in service at Bartow. The number of blade failures and problems with ST L-O blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-O fleet. The most common reported issue from the MHPS 40" L-O blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-O rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data analysis – learned (and made it known to Duke) that a significant contributing factor toward root cause of the L-O blade failures was extremely high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-O fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40" L-O fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

While Duke Engineering agrees that back-end loading should be considered a significant contributing factor toward root cause, one cannot definitively conclude that it has been the root cause of all five (5) of the documented L-O events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

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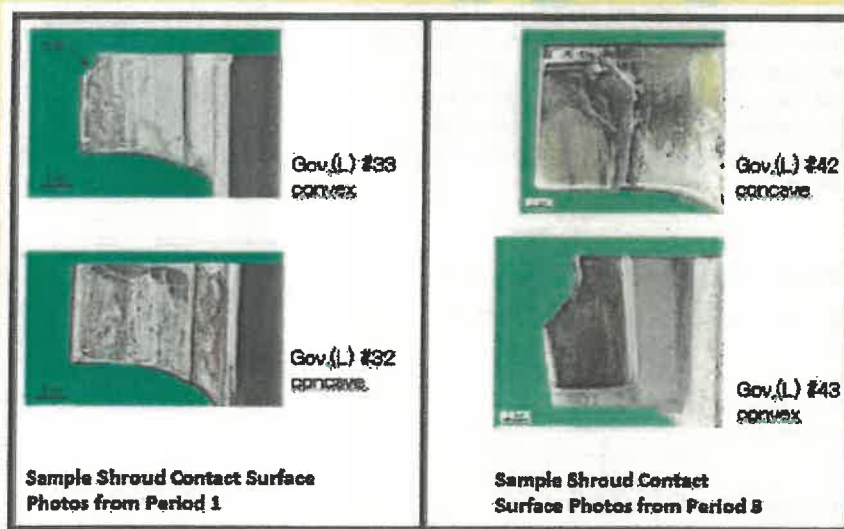
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By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours—2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1—a factor of 10 fewer hours for Period 3—there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Periods 1 and 3, photographic evidence suggests that the amount of wear is much greater for Period 3, as shown below in Figure 1. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

Figure 1 – Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern at the current LP Inlet operating limits. MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine

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beyond the current LP Inlet operating limits due to concerns for impacts to upstream blading – i.e. the L-1 blade sets.

Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact the L-0 blades. Since the design of the condenser includes spargers, or “dump tubes”, for the hot reheat (HRH) and LP bypass steam flows from each of the four combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or “counts”. “Counts” are defined as the number of measureable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Table 1 – Quick Comparison of the Number of “Counts” that Meet the Criteria for Periods 1-5.

	Number of Operating Hours in Each Period	Number of Blends (or “Counts”) Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

*Includes 6 blends that meet the criteria during strain gauge testing in December 2014

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is

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programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

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A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive periods. Maintenance of the hood sprays control valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the same control valve had filled with debris in prior years' operating.

Figure 2, below, demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

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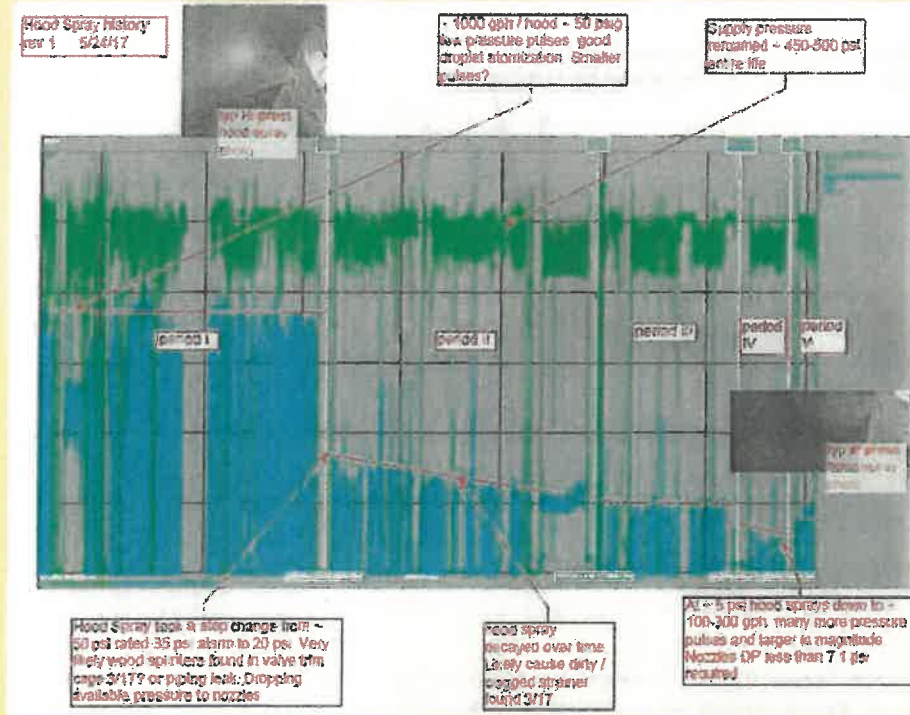
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Figure 2 -- Hood Spray Pressure Degradation Over Periods 1-5



Zone Analysis – Shroud Fretting Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, MHPS identified areas (referred to as "Zones") where blade response was high, but still below the OEM design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1 through Zone F3 (shown by the red rectangles in Figure 3, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period.

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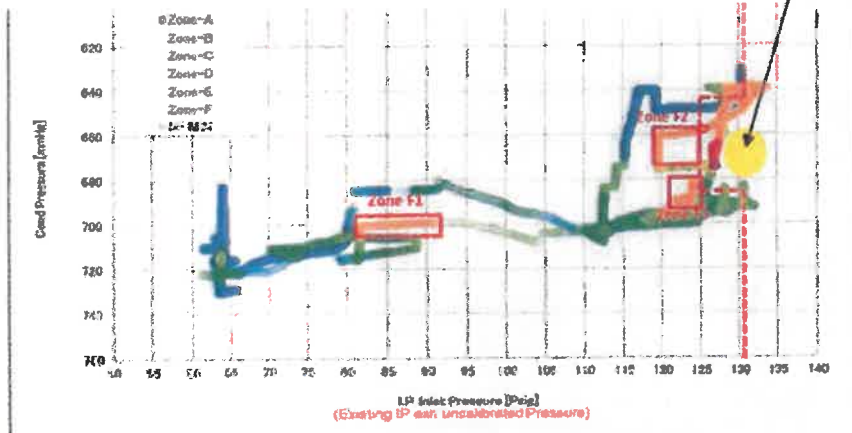
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Figure 3 – Data Presented by MHPS During a Presentation Dated 15 March 2017

Damage Mechanism

Blade Response – Design Margin
Example : Shroud Fretting Fatigue

Unable to test due to excessive blade response



- Blade response is evaluated through the integration of the stress response all the modes between 180Hz to 120Hz

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

Table 2 – Time (in Hours) Spent in Each Zone and the Total Compared with Operating Time

	Time in Zone			Total	Total Turbine Operating Hours	% Time in Zone F
	F1	F2	F3			
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

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The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure 4. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

Figure 4 -- Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear



Period 5 did have its share of higher energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending. The total of 20 hours of blend time does not appear to justify the wear seen.

Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers, which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting factor became the blade

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itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward root cause will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the root cause investigation between Periods 3 and 4, technical questions arose relative to “as left” blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren’t both taken into consideration together, then as the blades began to “untwist” as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture “worst case” geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

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Appendix A: Bartow L-0 Event Summary

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	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW (Nameplate)	420 MW	450 MW	450 MW	390 MW
Operating Restrictions	None - MHPS Intent Was to Follow Heat Balance Diagrams.	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111 psig Limit on IP Exhaust
Blade Overspeed Condition	Overspeed Testing in MFG		Overspeed Tested in Japan	No Overspeed Testing	No Overspeed Testing
Avoidance Zone Exceedance	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,264 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Parrot events	<p>MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, Ex1 heat balance) and to continue the warranty.</p> <p>MHPSA was storing for Tenaska (purchased grey market, stored by OEM).</p> <p>ST drawing modified by MHPSA and approved for Ex1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).</p>	<p>Not a forced outage. Outage planned to upgrade to "heavy duty" blades.</p> <p>Some blade damage (e.g. chipping at contact corners) was observed from removed service blades.</p> <p>Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.</p>	<p>During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits - unit ran in zone for <20 hrs.</p> <p>No blade cracking observed after testing (when the test instrumentation removed).</p>	<p>Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil.</p> <p>Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure.</p> <p>Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.</p>	<p>Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events.</p> <p>Jan 2017 "loss of mass" event - blade fragment projectile traveled through the LP turbine rupture disk diaphragm.</p> <p>Dental mold impression of failure surfaces indicate ~10^7 rotations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).</p>
Information Shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.

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Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	41"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	<i>Different Radial Height Relative to Bartow L-0 (About 1")</i>
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	No HVOF
Blade design	Orig.	Orig.	Orig.	<i>Attack Angle Change</i>
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	<i>In commissioning (~1yr)</i>
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

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Appendix C: Reference Materials

Mitsubishi RCA report – 9/22/2017

MHPS's evaluation is based on the data captured between Period 3 and 4 during blade telemetry testing. MHPS's evaluation is extensive and has allowed us to determine contributing factors. MHPS's intent was to draw conclusions based on actual data collected. The telemetry testing window was short not all operating conditions were witnessed during the testing (steady state and transient events); because of this the conclusions from this report may not be all encompassing of the drivers and conditions that are causing the blade failures.


Bartow RCA
Customer 9-22-17.pd

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Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0 blade failures during Period 1-5 is driven by evidence that the OEM designed last stage blades had little or no design margins for the actual operating conditions that exist for the overall Bartow 4 x 1 Combined Cycle Unit.

Duke Engineering believes the blade failures during Periods 1-5 involve more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.². Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. MHPS has since changed its position and today there is agreement between both parties that there is not just one failure mechanism.

After months of study (and with input from MHPS) Duke Engineering believes the following to be the most significant contributing factors toward blade failure over the history of Bartow Unit 4S L-0 events:

- Low Pressure (LP) Turbine Excessive Steam Flow
- Blending Operations – Thermal Distress (dT_{sh}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the brief period of time that the telemetry test conducted during December 2014. That blade response data was then extrapolated by MHPS Engineering to develop potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution for the Bartow LP section is to replace the L-0 blades or to retrofit the LP steam path with a more capable/reliable design. With either scenario, blade telemetry instrumentation and blade vibration monitoring will be necessary to conclusively determine and eliminate the magnitude and impact of the identified contributing factors during various operating configurations that are integral to unrestricted 4 x 1 combined cycle operation.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above. Any conclusions derived from Duke's efforts that are discussed in this document are based on the team's best ability to correlate data with events in operation and findings with L-0 blade inspections/failures.

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Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration.

Since commissioning there have been five (5) events triggered by L-O blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-O blade in efforts to address the failures (see Appendix B for L-O modifications). To date, the modifications have not resulted in improved reliability or performance of the L-O blades in service at Bartow. The number of blade failures and problems with ST L-O blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-O fleet. The most common reported issue from the MHPS 40" L-O blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-O rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data evaluation – learned (and made it known to Duke) that a significant contributing factor toward the L-O blade failures was extremely high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-O fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40" L-O fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

While Duke Engineering agrees that back-end loading should be considered a significant contributing factor toward the root cause, one cannot definitively conclude that it has been the failure driving mechanism of all five (5) of the documented L-O events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours – 2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

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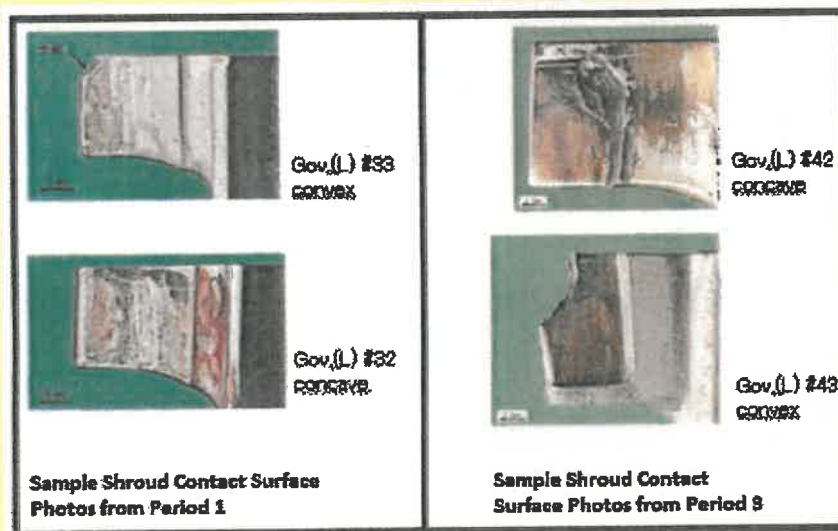
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Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1 – a factor of 10 fewer hours for Period 3 – there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Periods 1 and 3, photographic evidence suggests that the amount of wear is much greater for Period 3, as shown below in Figure 1. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

Figure 1 – Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern at the current LP inlet operating limits. MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current LP inlet operating limits due to concerns for impacts to upstream blading – i.e. the L-1 blade sets.

Blending Operations – Thermal Distress (dT₆₀/dt) at LP Turbine Exhaust

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During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact the L-0 blades. Since the design of the condenser includes spargers, or "dump tubes", for the hot reheat (HRH) and LP bypass steam flows from each of the four combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or "counts". "Counts" are defined as the number of measurable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Table 1 -- Quick Comparison of the Number of "Counts" that Meet the Criteria for Periods 1-5.

	Number of Operating Hours in Each Period	Number of Blends (or "Counts") Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

* Includes 6 blends that meet the criteria during strain gauge testing in December 2014

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

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A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

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Figure 2, below, demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

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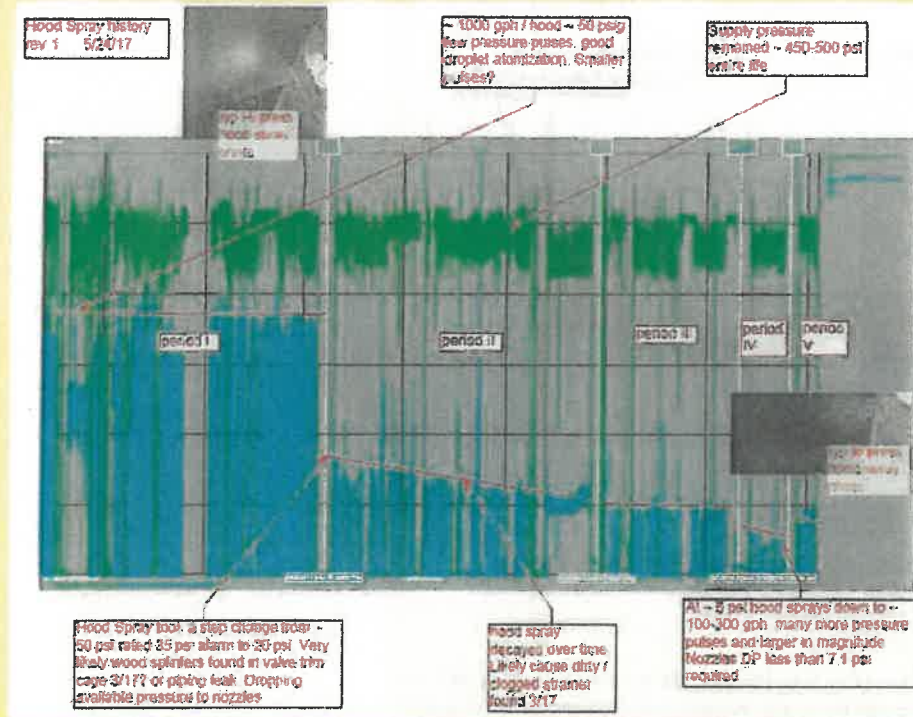
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Figure 2 -- Hood Spray Pressure Degradation Over Periods 1-5



Zone Analysis – Shroud Fretting Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, MHPS identified areas (referred to as "Zones") where blade response was high, but still below the OEM design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1 through Zone F3 (shown by the red rectangles in Figure 3, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period.

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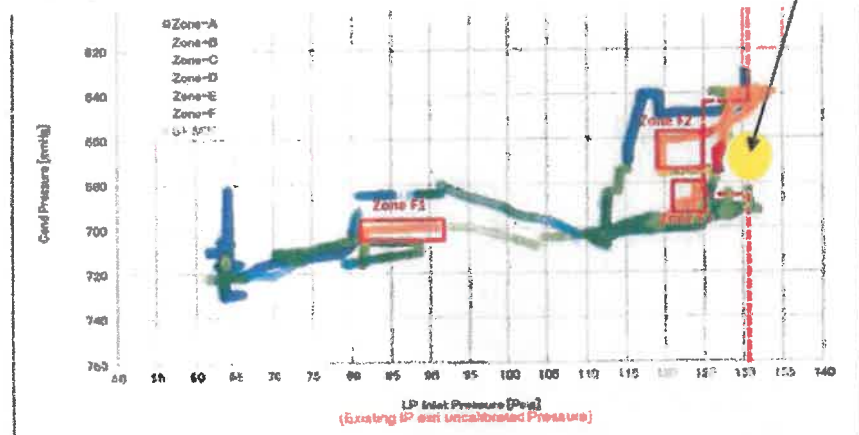
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Figure 3 – Data Presented by MHPS During a Presentation Dated 15 March 2017

Damage Mechanism

Blade Response – Design Margin
Example : Shroud Fretting Fatigue

Unable to test due to excessive blade response



- Blade response is evaluated through the integration of the stress response all the modes between 180Hz to 120Hz

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

Table 2 – Time (in Hours) Spent in Each Zone and the Total Compared with Operating Time

	Time in Zone				Total Turbine Operating Hours	% Time in Zone F
	F1	F2	F3	Total		
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

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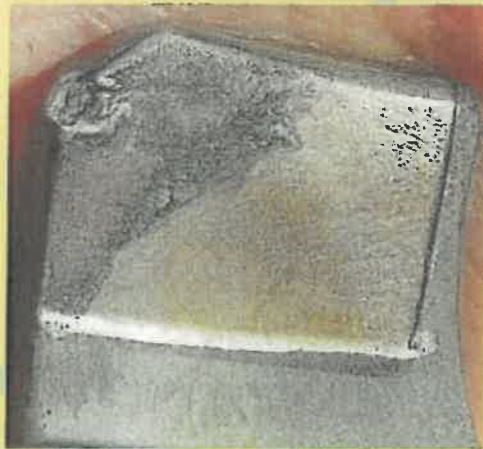
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The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure 4. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

Figure 4 -- Photo of an I-0 blade Z-Lock from Period 5 Showing Contact Surface Wear



Period 5 did have its share of higher energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending. The total of 20 hours of blend time does not appear to justify the wear seen.

Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers, which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting stress location became the

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blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward potential blade failure will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the RCA investigation between Periods 3 and 4, technical questions arose relative to “as left” blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren’t both taken into consideration together, then as the blades began to “untwist” as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture “worst case” geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

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Appendix A: Bartow L-0 Event Summary

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	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW (Nameplate)	420 MW	450 MW	450 MW	390 MW
Operating Restrictions	None - MHPS intent Was to Follow Heat Balance Diagrams.	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111 psig Limit on IP Exhaust
Blade Overspeed Condition	Overspeed Testing in MFG		Overspeed Tested in Japan	No Overspeed Testing	No Overspeed Testing
Avoidance Zone Exceedance	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,284 hrs.)	240 hrs. (of 10,286 hrs.)	135 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 19 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period events	<p>MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) and to continue the warranty.</p> <p>MHPSA was storing for Tenaska (purchased grey market, stored by OEM).</p> <p>ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph IP exhaust flow).</p>	<p>Not a forced outage. Outage planned to upgrade to "heavy duty" blades.</p> <p>Some blade damage (e.g. chipping at contact corners) was observed from removed service blades.</p> <p>Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 2.</p>	<p>During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits - unit ran in zone for <20 hrs.</p> <p>No blade cracking observed after testing (when the test instrumentation removed).</p>	<p>Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil.</p> <p>Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure.</p> <p>Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.</p>	<p>Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events.</p> <p>Jan 2017 "loss of mass" event - blade fragment projectile traveled through the IP turbine rupture disk diaphragm.</p> <p>Dental mold impression of failure surfaces indicate ~10^7 vibrations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).</p>
Information Shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.

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Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Class L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	<i>Different Radial Height Relative to Bartow L-0 (About 1")</i>
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	No HVOF
Blade design	Orig.	Orig.	Orig.	<i>Attack Angle Change</i>
Experience	3 units (2003)	12 units (2003)	1 unit, ~5 months	<i>In commissioning ~1yr</i>
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

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Appendix C: Reference Materials

Mitsubishi RCA report -- 9/22/2017

MHPS's evaluation is based on the data captured between Period 3 and 4 during blade telemetry testing. MHPS's evaluation is extensive and has allowed us to determine contributing factors. MHPS's intent was to draw conclusions based on actual data collected. The telemetry testing window was short not all operating conditions were witnessed during the testing (steady state and transient events); because of this the conclusions from this report may not be all encompassing of the drivers and conditions that are causing the blade failures.


Bartow RCA
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Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0 blade failures during Period 1-5 is driven by evidence that the OEM designed last stage blades had little or no design margins for the actual operating conditions that exist for the overall Bartow 4 x 1 Combined Cycle Unit.

Duke Engineering believes the blade failures during Periods 1-5 involve more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.². Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. MHPS has since changed its position and today there is agreement between both parties that there is not just one failure mechanism.

After months of study (and with input from MHPS) Duke Engineering believes the following to be the most significant contributing factors toward blade failure over the history of Bartow Unit 4S L-0 events:

- Low Pressure (LP) Turbine Excessive Steam Flow
- Blending Operations – Thermal Distress (dT_{ex}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the brief period of time that the telemetry test conducted during December 2014. That blade response data was then extrapolated by MHPS Engineering to develop potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution for the Bartow LP section is to replace the L-0 blades or to retrofit the LP steam path with a more capable/reliable design. With either scenario, blade telemetry instrumentation and blade vibration monitoring will be necessary to conclusively determine and eliminate the magnitude and impact of the identified contributing factors during various operating configurations that are integral to unrestricted 4 x 1 combined cycle operation.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above. Any conclusions derived from Duke's efforts that are discussed in this document are based on the team's best ability to correlate data with events in operation and findings with L-0 blade inspections/failures.

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- Blending Operations – Thermal Distress (dt_{sh}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
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- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
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Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration.

Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical - i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering - through data evaluation - learned (and made it known to Duke) that a significant contributing factor toward the L-0 blade failures was high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve - the lone exception being "brief" operation during transient conditions.

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While Duke Engineering agrees that back-end loading should be considered a significant contributing factor, one cannot definitively conclude that it has been the failure driving mechanism of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

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By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours - 2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

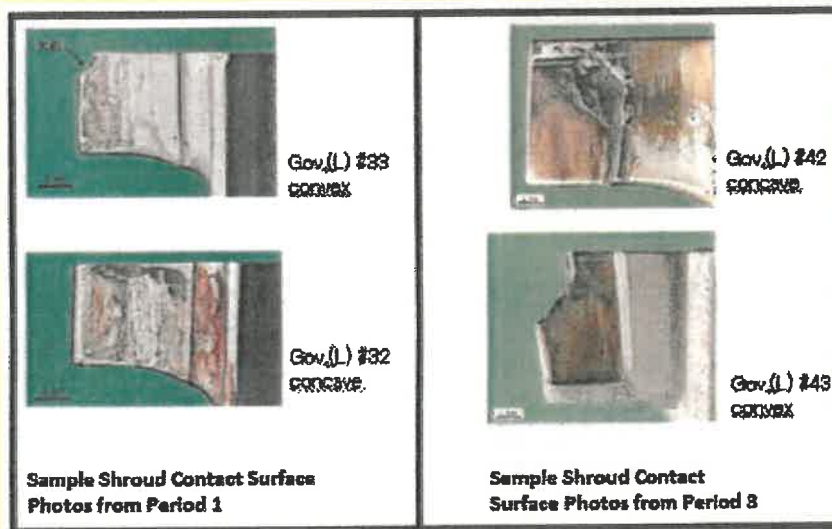
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Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1 -- a factor of 10 fewer hours for Period 3 -- there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Periods 1 and 3, photographic evidence suggests that the amount of wear is much greater for Period 3, as shown below in Figure 1. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

Figure 1 -- Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern at the current LP inlet operating limits. MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current LP inlet operating limits due to concerns for impacts to upstream blading -- i.e. the L-1 blade sets.

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Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact exhaust conditions of the LP. Since the design of the condenser includes spargers, or “dump tubes”, for the hot reheat (HRH) and LP bypass steam flows from each of the four combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or “counts”. “Counts” are defined as the number of measurable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Table 1 -- Quick Comparison of the Number of “Counts” that Meet the Criteria for Periods 1-5.

	Number of Operating Hours in Each Period	Number of Blends (or “Counts”) Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

*Includes 6 blends that meet the criteria during strain gauge testing in December 2014

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

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If I am off base don't change it.

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Commented [MB2]: We don't really conclude anything with this section. Do we need a to add that until we install blades with telemetry testing we will not understand the total impact of this thermal energy on the blades. This was reviewed by MHPs during the previous blade telemetry test and they were not able to conclude a result. To be noted: not all blend conditions and configurations were exercised during the telemetry testing so there is not enough evidence to prove or refute this contributing factor.

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A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

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During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an Instrumentation issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the hood sprays control valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the same control valve had filled with debris in prior years' operating.

Figure 2, below, demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

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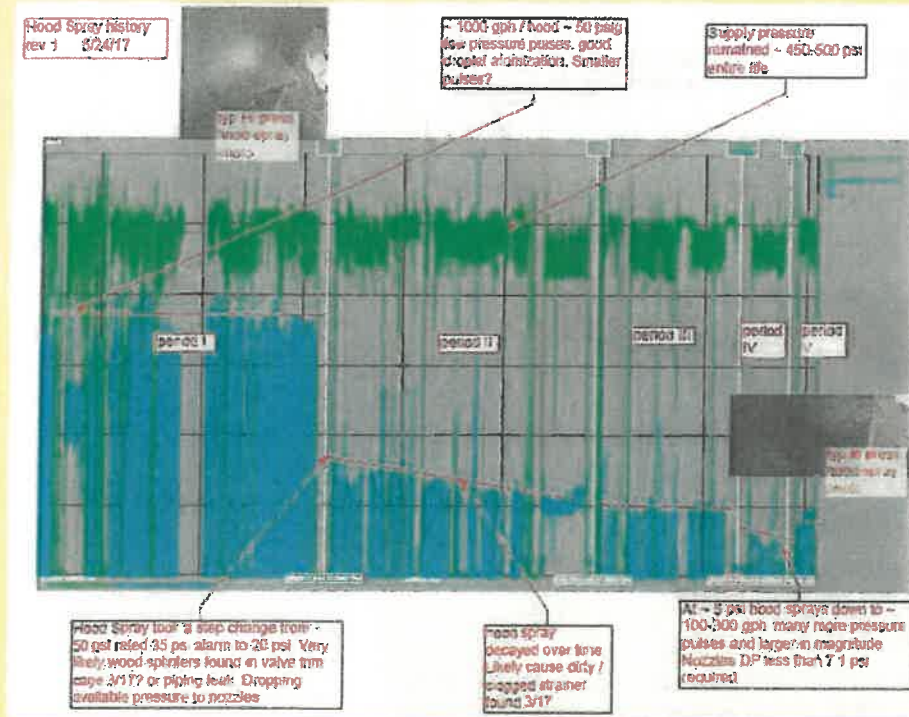
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Figure 2 – Hood Spray Pressure Degradation Over Periods 1-5



Zone Analysis – Shroud Fretting Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, MHPS identified areas (referred to as "Zones") where blade response was high, but still below the OEM design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1 through Zone F3 (shown by the red rectangles in Figure 3, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period. MHPS did not provide any restriction of operation in Zones F1 through F3, only the exclusion zone identified by the dotted red line in Figure 3.

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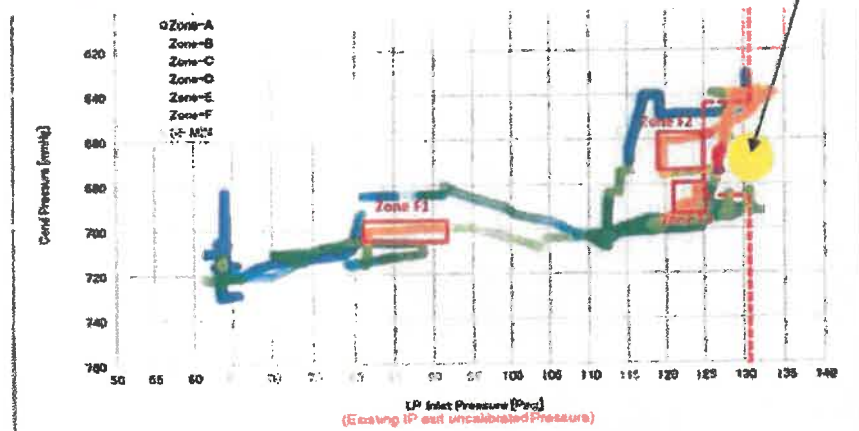
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Figure 3 -- Data Presented by MHP5 During a Presentation Dated 15 March 2017

Damage Mechanism

Blade Response – Design Margin
Example : Shroud Fretting Fatigue

Unable to test due to excessive blade response



- Blade response is evaluated through the integration of the stress response all the modes between 180Hz to 120Hz

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

Table 2 – Time (in Hours) Spent in Each F1 and the Total Compared with Operating Time

	Time in Zone				Total Turbine Operating Hours	% Time in Zone F
	F1	F2	F3	Total		
Period 1	901.2	257.5	23.9	1182.6	21794	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
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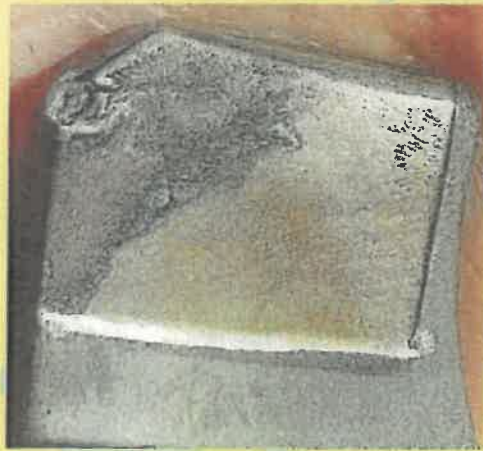
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The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure 4. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

Figure 4 -- Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear



Period 5 did have high energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending as compare to time operated in Zone F1.

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Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

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The loss of dampening phenomena was a contributing factor during Periods 3 and 4. HVOF hard-facing can reduce the amount of base material fretting during operation. The application of HVOF is used on many applications in the industry for blading contact surfaces. When applied the HVOF hard-facing changes the frictional forces of the contact surface reducing fretting and has an increased hardness to prevent material loss.

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For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers, which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

Commented [MBS]: Do we need this? To help quantify why dampening is reduced with hard-facing? Might need to run the wording by Paul/Henry for accuracy.

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For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting stress location became the blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward potential blade failure will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the RCA investigation between Periods 3 and 4, technical questions arose relative to “as left” blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren’t both taken into consideration together, then as the blades began to “untwist” as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture “worst case” geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with Independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a [new](#) Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

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Appendix A: Bartow L-0 Event Summary

Commented [MB6]: Is your excel summary of the better than this table or can it be in addition to this table? Key notes and other comments should be reviewed closely to make sure they don't contradict whats above. This was written before we knew a lot.

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW (Nameplate)	420 MW	450 MW	450 MW	390 MW
Operating Restrictions	None - MHPS Intent Was to Follow Heat Balance Diagrams.	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111 psig Limit on IP Exhaust
Blade Overspeed Condition	Overspeed Testing in MFG		Overspeed Tested in Japan	No Overspeed Testing	No Overspeed Testing
Avoidance Zone Exceedance	2,466 hrs. (of 23,734 hrs.)	1 hr. (of 23,284 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 3,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period events	<p>MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) and to continue the warranty.</p> <p>MHPSA was storing for Tenaska (purchased grey market, stored by OEM).</p> <p>ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).</p>	<p>Not a forced outage. Outage planned to upgrade to "heavy duty" blades.</p> <p>Some blade damage (e.g. chipping at contact points) was observed from removed service blades.</p> <p>Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.</p>	<p>During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits - unit ran in zone for <20 hrs.</p> <p>No blade cracking observed after testing (when the test instrumentation removed).</p>	<p>Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil.</p> <p>Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure.</p> <p>Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.</p>	<p>Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events.</p> <p>Jan 2017 "loss of mass" event - blade fragment projectile traveled through the LP turbine rupture disk diaphragm.</p> <p>Dental mold impression of failure surfaces indicate ~10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).</p>
Information Shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.

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Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	<i>Different Radial Height Relative to Bartow L-0 (About 1")</i>
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	No HVOF
Blade design	Orig.	Orig.	Orig.	<i>Attack Angle Change</i>
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	<i>in commissioning (~1yr)</i>
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

Commented [MB7]: You mentioned Type 5 above. Is the redesign blade for Bartow different than Citrus? Sounded like MHPS was "designing" something new for Bartow. If it's the citrus blade then there should have been no slide on the changes being made (in the MHPS root cause). Maybe this isn't a type 5, but the "latest Gen 40" blade??

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Appendix C: Reference Materials

Mitsubishi RCA report – 9/22/2017

MHPS's evaluation is based on the data captured between Period 3 and 4 during blade telemetry testing. MHPS's evaluation is extensive and has allowed us to identify and evaluate contributing factors. MHPS's intent was to draw conclusions based on actual data collected. The telemetry testing window was short not all operating conditions were witnessed during the testing (steady state and transient events); because of this the conclusions from this report may not be all encompassing of the drivers and conditions that are causing the blade failures.

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Bartow RCA
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Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0 blade failures during Period 1-5 is driven by evidence that the OEM designed last stage blades had little or no design margins for the actual operating conditions that exist for the overall Bartow 4 x 1 Combined Cycle Unit.

Duke Engineering believes the blade failures during Periods 1-5 involve more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.². Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. MHPS has since changed its position and today there is agreement between both parties that there is not just one simple failure driving mechanism.

After months of study (and with input from MHPS) Duke Engineering believes the following to be the most significant contributing factors toward blade failure over the history of Bartow Unit 4S L-0 events:

- Low Pressure (LP) Turbine Excessive Steam Flow
- Blending Operations – Thermal Distress (dT_{sh}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the brief period of time that the telemetry test conducted during December 2014. That blade response data was then extrapolated by MHPS Engineering to develop potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution for the Bartow LP section is to replace the L-0 blades or to retrofit the LP steam path with a more capable/reliable design. With either scenario, blade telemetry instrumentation and blade vibration monitoring will be necessary to conclusively determine and eliminate the magnitude and impact of the identified contributing factors during various operating configurations that are integral to unrestricted 4 x 1 combined cycle operation.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above. Any conclusions derived from Duke's efforts that are discussed in this document are based on the team's best ability to correlate data with events in operation and findings with L-0 blade inspections/failures.

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Executive Summary

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Duke Engineering believes the blade failures during Periods 1-5 involve more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.². Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. MHPS has since changed its position and today there is agreement between both parties that there is not just one failure mechanism.

After months of study (and with input from MHPS) Duke Engineering believes the following to be the most significant contributing factors toward blade failure over the history of Bartow Unit 4S L-O events:

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- Blending Operations – Thermal Distress (dT_{sh}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the brief period of time that the telemetry test conducted during December 2014. That blade response data was then extrapolated by MHPS Engineering to develop potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution for the Bartow LP section is to replace the L-O blades or to retrofit the LP steam path with a more capable/reliable design. With either scenario, blade telemetry instrumentation and blade vibration monitoring will be necessary to conclusively determine and eliminate the magnitude and impact of the identified contributing factors during various operating configurations that are integral to unrestricted 4 x 1 combined cycle operation.

This technical paper will speak briefly of the history of L-O blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above. Any conclusions derived from Duke's efforts that are discussed in this document are based on the team's best ability to correlate data with events in operation and findings with L-O blade inspections/failures.

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Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration.

Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data evaluation – learned (and made it known to Duke) that a significant contributing factor toward the L-0 blade failures was high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

While Duke Engineering agreed that back-end loading should be considered a significant contributing factor, one cannot definitively conclude that it has been the failure driving mechanism of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours – 2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

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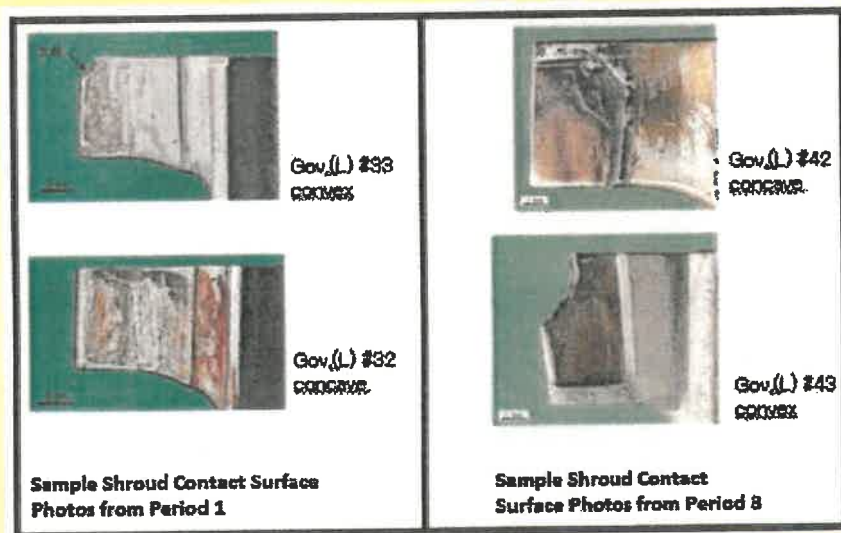
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Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1 – a factor of 10 fewer hours for Period 3 – there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Periods 1 and 3, photographic evidence suggests that the amount of wear is much greater for Period 3, as shown below in Figure 1. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

Figure 1 -- Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern at the current LP inlet operating limits. MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current LP inlet operating limits due to concerns for impacts to upstream blading – i.e. the L-1 blade sets.

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Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact exhaust conditions of the LP. Since the design of the condenser includes spargers, or "dump tubes", for the hot reheat (HRH) and LP bypass steam flows from each of the four combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or "counts". "Counts" are defined as the number of measurable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Table 1 – Quick Comparison of the Number of "Counts" that Meet the Criteria for Periods 1-5.

	Number of Operating Hours in Each Period	Number of Blends (or "Counts") Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

*Includes 6 blends that meet the criteria during strain gauge testing in December 2014

Commented [MB1]: We don't really conclude anything with this section. Do we need to add that until we install blades with telemetry testing we will not understand the total impact of this thermal energy on the blades. This was reviewed by MHPs during the previous blade telemetry test and they were not able to conclude a result. To be noted: not all blend conditions and configurations were exercised during the telemetry testing so there is not enough evidence to prove or refute this contributing factor

Pressure Pulses During Hood/Curtain Spray Operations

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

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A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the hood sprays control valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the same control valve had filled with debris in prior years' operating.

Figure 2, below, demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-O blades might see as large water droplets evaporate in the exhaust stream.

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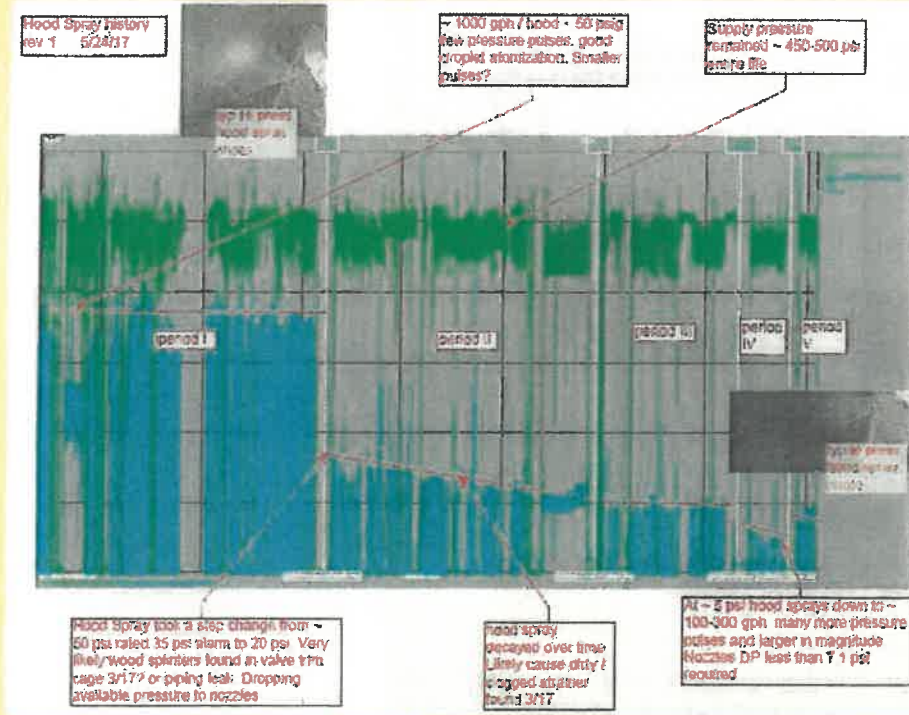
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Figure 2 – Hood Spray Pressure Degradation Over Periods 1-5



Zone Analysis – Shroud Fretting Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, the OEM identified areas (referred to as “Zones”) where blade response was high, but still below the OEM design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1, Zone F2, and Zone F3 (shown by the red rectangles in Figure 3, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period. The OEM did not provide any restriction(s) to operation in Zone F1, Zone F2, and/or Zone F3 – only restrictions relative to “operation in the avoidance zone” identified by the area of the graph to the right of the dotted red line in Figure 3.

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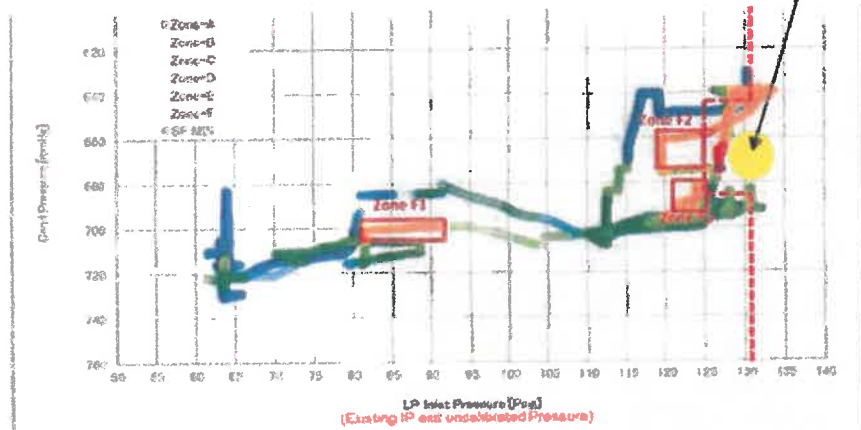
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Figure 3 – Data Presented by MHPS During a Presentation Dated 15 March 2017

Damage Mechanism

Blade Response – Design Margin
Example : Shroud Fretting Fatigue

Unable to test due to excessive blade response



- Blade response is evaluated through the integration of the stress response all the modes between 180Hz to 120Hz

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

Table 2 – Time (in Hours) Spent in Each Zone and the Total Compared with Operating Time

	Time in Zone			Total	Total Turbine Operating Hours	% Time in Zone F
	F1	F2	F3			
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

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The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure 4. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

Figure 4 -- Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear



Period 5 did have high energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending as compared to operating hours in Zone F1.

Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

HVOF hard-facing can reduce the amount of base material fretting during operation and is used on many applications across the industry for blading contact surfaces. When applied, the HVOF hard-facing changes the frictional forces of the contact surface reducing fretting and has an increased hardness to prevent material loss.

The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers, which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

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For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting stress location became the blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward potential blade failure will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the RCA investigation between Periods 3 and 4, technical questions arose relative to “as left” blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren’t both taken into consideration together, then as the blades began to “untwist” as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

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While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a new Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

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Appendix A: Bartow L-O Event Summary

Commented [MB2]: Is your excel summary of the better than this table or can it be in addition to this table? Key notes and other comments should be reviewed closely to make sure they don't contradict whats above. This was written before we knew a lot.

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-O Blade Configuration	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW (Nameplate)	420 MW	450 MW	450 MW	390 MW
Operating Restrictions	None - MHPS Intent Was to Follow Heat Balance Diagrams.	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111 psig Limit on IP Exhaust
Blade Overspeed Condition	Overspeed Testing in MFG		Overspeed Tested in Japan	No Overspeed Testing	No Overspeed Testing
Avoidance Zone Exceedance	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,284 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	94 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period events	<p>MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) had to continue the warranty.</p> <p>MHPSA was storing for Tenaska (purchased grey market, stored by OEM).</p> <p>ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).</p>	<p>Not a forced outage. Outage planned to upgrade to "heavy duty" blades.</p> <p>Some blade damage (e.g chipping at contact corners) was observed from removed service blades.</p> <p>Blade telemetry instrumentation installed and testing conducted in Dec'2014 at the beginning of Period 3.</p>	<p>During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits - unit ran in zone for <20 hrs.</p> <p>No blade cracking observed after testing (when the test instrumentation removed).</p>	<p>Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil.</p> <p>Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure.</p> <p>Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.</p>	<p>Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-O events.</p> <p>Jan 2017 "loss of mass" event - blade fragment projectile traveled through the LP turbine rupture disk diaphragm.</p> <p>Dental mold impression of failure surfaces indicate ~10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).</p>
Information Shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.

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Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turby/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	<i>Different Radial Height Relative to Bartow L-0 (About 1")</i>
Z-lock	No HVOF	No HVOF	45° Corner with HVOF Applied	No HVOF
Blade design	Orig.	Orig.	Orig.	<i>Attack Angle Change</i>
Experience	3 units (2003)	12 units (2003)	1 unit ~5 months	<i>In commission ~1yr</i>
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

Commented [MB3]: You mentioned Type 5 above is the redesign blade for Bartow different than Citrus? Sounded like MHPS was "designing" something new for Bartow. If it's the citrus blade then there should have been no slide on the changes being made (in the MHPS root cause) Maybe this isn't a type 5, but the "latest Gen 40" blade??

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Appendix C: Reference Materials

Mitsubishi RCA report – 9/22/2017

MHPS's evaluation is based on the data captured between Period 2 and 3 during blade telemetry testing. MHPS's evaluation is extensive and has allowed us to identify and evaluate contributing factors. MHPS's intent was to draw conclusions based on actual data collected. The telemetry testing window was short not all operating conditions were witnessed during the testing (steady state and transient events); because of this the conclusions from this report may not be all encompassing of the drivers and conditions that are causing the blade failures.


Bartow RCA
Customer 9-22-17.pd

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Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0 blade failures during Period 1-5 is driven by evidence that the OEM designed last stage blades had little or no design margins for the actual operating conditions that exist for the overall Bartow 4 x 1 Combined Cycle Unit.

Duke Engineering believes the blade failures during Periods 1-5 involve more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.². Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. MHPS has since changed its position and today there is agreement between both parties that there is not just one failure mechanism.

After months of study (and with input from MHPS) Duke Engineering believes the following to be the most significant contributing factors toward blade failure over the history of Bartow Unit 4S L-0 events:

- Low Pressure (LP) Turbine Excessive Steam Flow
- Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the brief period of time that the telemetry test conducted during December 2014. That blade response data was then extrapolated by MHPS Engineering to develop potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution for the Bartow LP section is to replace the L-0 blades or to retrofit the LP steam path with a more capable/reliable design. With either scenario, blade telemetry instrumentation and blade vibration monitoring will be necessary to conclusively determine and eliminate the magnitude and impact of the identified contributing factors during various operating configurations that are integral to unrestricted 4 x 1 combined cycle operation.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above. Any

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Executive Summary

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conclusions derived from Duke's efforts that are discussed in this document are based on the team's best ability to correlate data with events in operation and findings with L-0 blade inspections/failures.

Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration.

Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

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Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data evaluation – learned (and made it known to Duke) that a significant contributing factor toward the L-0 blade failures was high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

While Duke Engineering agreed that back-end loading should be considered a significant contributing factor, one cannot definitively conclude that it has been the failure driving mechanism of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours – 2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a

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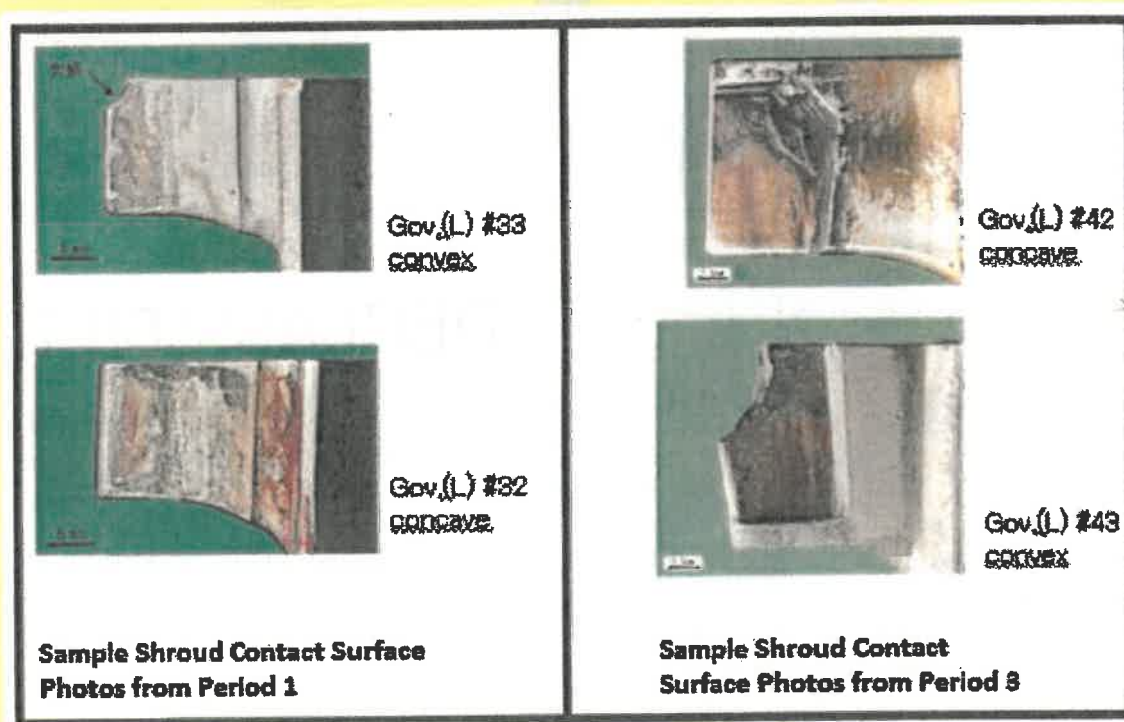
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minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1 – a factor of 10 fewer hours for Period 3 – there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Periods 1 and 3, photographic evidence suggests that the amount of wear is much greater for Period 3, as shown below in Figure 1. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

Figure 1 – Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern at the current LP inlet operating limits. MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current LP inlet operating limits due to concerns for impacts to upstream blading – i.e. the L-1 blade sets.

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Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact exhaust conditions of the LP. Since the design of the condenser includes spargers, or “dump tubes”, for the hot reheat (HRH) and LP bypass steam flows from each of the four (4) combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or “counts”. “Counts” are defined as the number of measurable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Table 1 – Quick Comparison of the Number of “Counts” that Meet the Criteria for Periods 1-5.

	Number of Operating Hours in Each Period	Number of Blends (or “Counts”) Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

*Includes 6 blends that meet the criteria during strain gauge testing in December 2014

Until a long term solution other than the pressure plate is installed into the machine and the turbine is appropriately equipped with strain gauge and blade vibration monitoring hardware, Duke will not fully understand the total impact of this thermal energy on the blades. Duke Engineering believes that the brief telemetry testing period conducted in December 2014 does not – by itself – provide conclusive enough evidence to support (or refute) this contributing factor of thermal distress, as not all blend conditions and configurations were exercised during the testing period

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Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

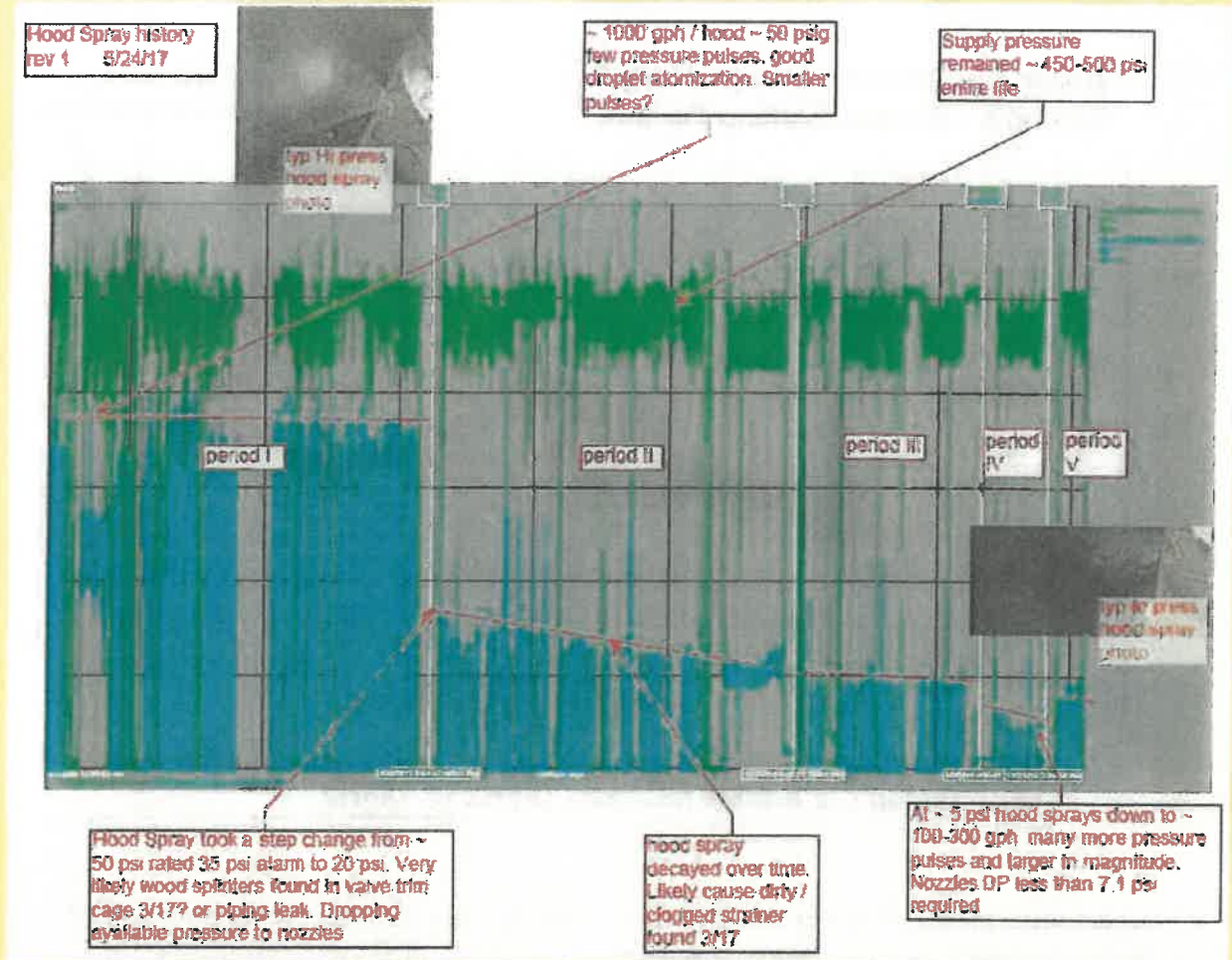
During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the hood sprays control valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the same control valve had filled with debris in prior years' operating.

Figure 2, below, demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization through centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

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Figure 2 -- Hood Spray Pressure Degradation Over Periods 1-5



Zone Analysis – Shroud Fretting Fatigue

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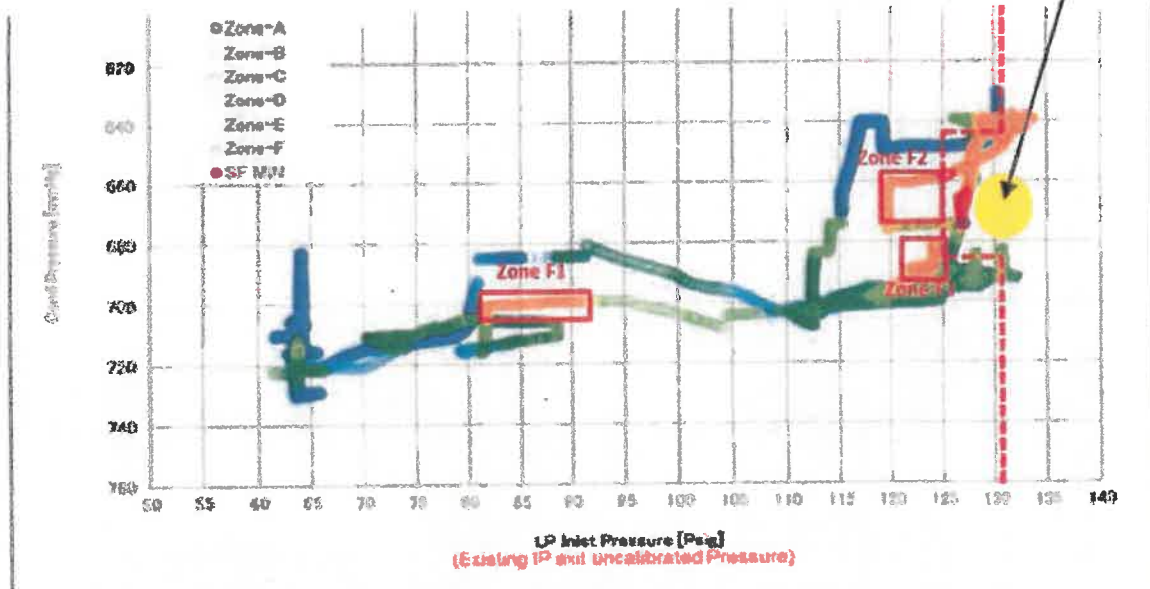
Based on data from the Period 3 blade strain gauge test in December 2014, the OEM identified areas (referred to as “Zones”) where blade response was high, but still below the OEM design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1, Zone F2, and Zone F3 (shown by the red rectangles in Figure 3, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period. The OEM did not provide any restriction(s) to operation in Zone F1, Zone F2, and/or Zone F3 – only restrictions relative to “operation in the avoidance zone” identified by the area of the graph to the right of the dotted red line in Figure 3.

Figure 3 – Data Presented by MHPS During a Presentation Dated 15 March 2017

Damage Mechanism

Blade Response – Design Margin
Example : Shroud Fretting Fatigue

Unable to test due to excessive blade response



- Blade response is evaluated through the integration of the stress response all the modes between 180Hz to 120Hz

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

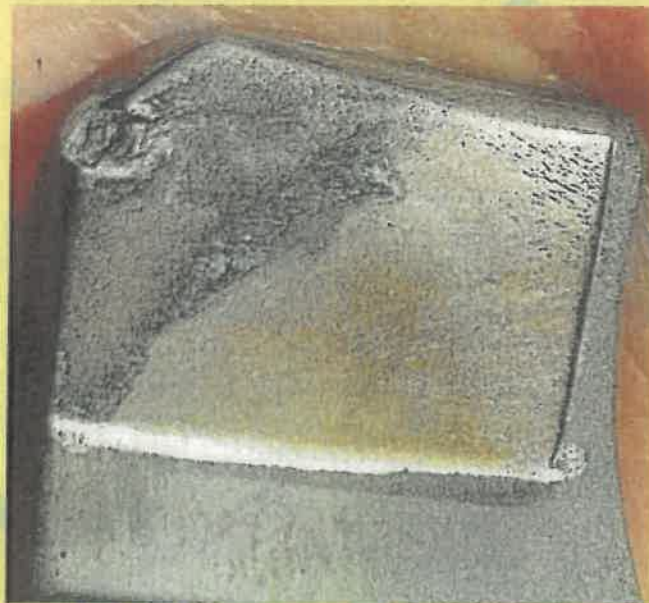
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Table 2 – Time (in Hours) Spent in Each Zone and the Total Compared with Operating Time

	Time in Zone				Total Turbine Operating Hours	% Time in Zone F
	F1	F2	F3	Total		
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure 4. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

Figure 4 -- Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear



Period 5 did have high energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending as compared to operating hours in Zone F1.

Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

HVOF hard-facing can reduce the amount of base material fretting during operation and is used on many applications across the industry for blading contact surfaces. When applied, the HVOF hard-facing changes the frictional forces of the contact surface reducing fretting and has an increased hardness to prevent material loss.

The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers,

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which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting stress location became the blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward potential blade failure will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the RCA investigation between Periods 3 and 4, technical questions arose relative to “as left” blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren’t both taken into consideration together, then as the blades began to “untwist” as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture “worst case” geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

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Appendix A: Bartow L-0 Event Summary

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Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfalls	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period events	<p>MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) and to continue the warranty.</p> <p>MHPSA was storing for Tenaska (purchased grey market, stored by OEM).</p> <p>ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mph LP exhaust flow).</p>	<p>Not a forced outage – Outage planned to upgrade to "heavy duty" blades.</p> <p>Some blade damage (e.g. chipping at contact corners) was observed from removed service blades.</p> <p>Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.</p>	<p>During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits – unit ran in zone for <20 hrs.</p> <p>No blade cracking observed after testing (when the test instrumentation removed).</p>	<p>Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil.</p> <p>Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure.</p> <p>Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.</p>	<p>Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events.</p> <p>Jan 2017 "loss of mass" event – blade fragment projectile traveled through the LP turbine rupture disk diaphragm.</p> <p>Dental mold impression of failure surfaces indicate ~10⁷ striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).</p>
Information Shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.

Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	<i>Different Radial Height Relative to Bartow L-0 (About 1")</i>
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	No HVOF
Blade design	Original	Original	Original	<i>Attack Angle Change</i>
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

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Appendix C: Empirical Data Supporting Root Cause

Empirical Support for Root Cause

Period	Operating Hours	Excessive Steam Flow			Normalized Ranking
		Driving Mechanism Present	Avoidance Zone Exceedance Hours	Exceedance Hours / (1k Operating Hours)	
1	21,734	X	2,466	0.11	1.00
2	21,284		3	0.00	0.00
3	10,286	X	240	0.02	0.21
4*	2,942		1	0.00	0.00
5	1,561		0	0.00	0.00

Period	Operating Hours	Thermal Distress (dT ₁₀ /dt)			Normalized Ranking
		Driving Mechanism Present	Counts (ΔT > 20 deg. F ₁₀ / Minutes)	Counts / (1k Operating Hours)	
1	21,734	X	13	0.60	0.17
2	21,284	X	7	0.33	0.09
3	10,286	X	37	3.60	1.00
4*	2,942	X	8	2.02	0.28
5	1,561	X	5	3.20	0.89

Period	Operating Hours	Pressure Pulses				Normalized Ranking
		Driving Mechanism Present	Avg. Hood Spray Pressure (psig)	Hours of Hood Spray Operation	% of Total Operating Hours	
1	21,734	X	35.2	5,098	23	0.69
2	21,284	X	19.2	7,345	34	1.00
3	10,286	X	10.4	440	4	0.12
4*	2,942	X	5.5	174	6	0.17
5	1,561	X	8.7	93	6	0.17

Period	Operating Hours	Loss of Dampening
		Driving Mechanism Present
1	21,734	N/A
2	21,284	N/A
3	10,286	N/A**
4*	2,942	X
5	1,561	N/A

Period 1	Jun 2009 to Mar 2012
Period 2	Apr 2012 to Aug 2014
Period 3	Dec 2014 to Apr 2016
Period 4	Jun 2016 to Oct 2016
Period 5	Dec 2016 to Feb 2017

General Notes

* For Period 4, the first L-0 blade tip was lost on 7/6/16 at about 10:50AM -- BEFORE 1st thermal event on 7/16/16 and BEFORE operation above "avoidance zone" limit on 08/01 - 9/25/16 (55 min total).

"Excessive Steam Flow" Notes

"Avoidance Zone Exceedance Hours" -- Measured number of operating hours in exceedance of 15,000 lb/hr-ft² limit as indicated by the IP exhaust pressure

"Exceedance Hours / (1k Operating Hours)" -- Number of exceedance hours per 1000 hours of operation in a given period

"Normalized Ranking" -- Data normalized against the highest value in Column F

"Thermal Distress (dT₁₀/dt)" Notes

"Counts (DT > 20 deg. FSH / Minute)" -- "Counts" are defined as the number of measurable blends where there was a slope change (+/-) greater than (20 degrees superheat / min) at the hood spray thermocouples -- Data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW

"Counts / (1k Operating Hours)" -- Number of "counts" per 1000 hours of operation in a given period

"Normalized Ranking" -- Data normalized against the highest value in Column F

"Pressure Pulses" Notes

"Avg. Hood Spray Pressure (psig)" -- Calculated from PI historian data (???) -- Verify

"Hours of Hood Spray Operation" -- "Hours of Hood Spray Operation" is a weighted value -- There is a 1.00 multiplier at 50 psig varying linearly to a 1.75 multiplier at 5 psig

"% of Total Operating Hours" -- The "weighted" hours of hood spray operation divided by the total number of operating hours -- converted to a percentage value

"Normalized Ranking" -- Data normalized against the highest percentage value in Column G

"Loss of Dampening" Notes

** For Period 3, there was hard-facing on the Mid-span toubber ONLY -- Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was likely due to loss of dampening of the snubbers, which were HVOC-coated -- The Z-Lock contact surfaces were torqued to provide all of the dampening for the system via additional motion

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Appendix D: Reference Materials

Mitsubishi RCA Presentation(s) – 22 September 2017 and 02 October 2017

MHPS's evaluation is based on the data captured between Period 2 and 3 during blade telemetry testing. MHPS's evaluation is extensive and has allowed us to identify and evaluate contributing factors. MHPS's intent was to draw conclusions based on actual data collected. The telemetry testing window was short, and not all operating conditions were witnessed during the testing (steady state and transient events). Because of this the conclusions from this report may not be all encompassing of the drivers and conditions that are causing the blade failures.



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Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0 blade failures during Period 1-5 is driven by evidence that the OEM designed last stage blades had little or no design margins for the actual operating conditions that exist for the overall Bartow 4 x 1 Combined Cycle Unit.

Duke Engineering believes the blade failures during Periods 1-5 involve more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.². Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. MHPS has since changed its position and today there is agreement between both parties that there is not just one failure mechanism.

After months of study (and with input from MHPS) Duke Engineering believes the following to be the most significant contributing factors toward blade failure over the history of Bartow Unit 4S L-0 events:

- Low Pressure (LP) Turbine Excessive Steam Flow
- Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the brief period of time that the telemetry test conducted during December 2014. That blade response data was then extrapolated by MHPS Engineering to develop potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution for the Bartow LP section is to replace the L-0 blades or to retrofit the LP steam path with a more capable/reliable design. With either scenario, blade telemetry instrumentation and blade vibration monitoring will be necessary to conclusively determine and eliminate the magnitude and impact of the identified contributing factors during various operating configurations that are integral to unrestricted 4 x 1 combined cycle operation.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above. Any

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conclusions derived from Duke's efforts that are discussed in this document are based on the team's best ability to correlate data with events in operation and findings with L-0 blade inspections/failures.

Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration.

Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data evaluation – learned (and made it known to Duke) that a significant contributing factor toward the L-0 blade failures was high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.² (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.²). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

While Duke Engineering agreed that back-end loading should be considered a significant contributing factor, one cannot definitively conclude that it has been the failure driving mechanism of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours – 2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a

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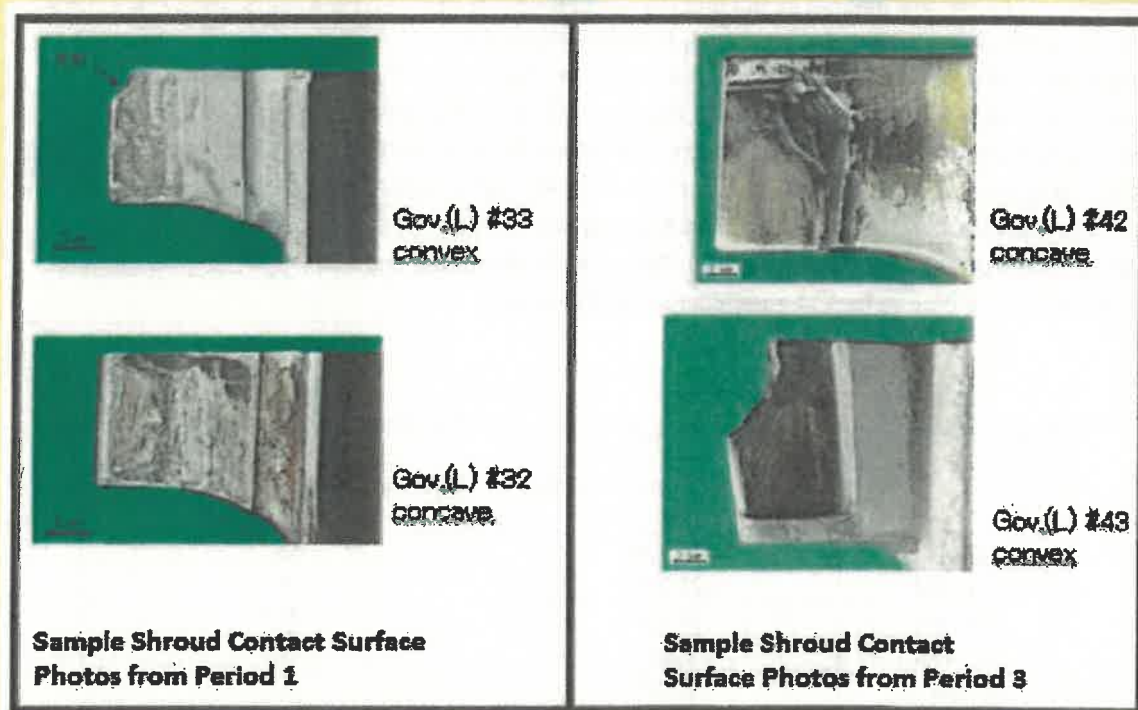
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minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1 – a factor of 10 fewer hours for Period 3 – there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Periods 1 and 3, photographic evidence suggests that the amount of wear is much greater for Period 3, as shown below in Figure 1. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

Figure 1 – Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern at the current LP inlet operating limits. MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current LP Inlet operating limits due to concerns for impacts to upstream blading – i.e. the L-1 blade sets.

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Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact exhaust conditions of the LP. Since the design of the condenser includes spargers, or “dump tubes”, for the hot reheat (HRH) and LP bypass steam flows from each of the four (4) combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or “counts”. “Counts” are defined as the number of measureable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Table 1 – Quick Comparison of the Number of “Counts” that Meet the Criteria for Periods 1-5.

	Number of Operating Hours in Each Period	Number of Blends (or “Counts”) Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

*Includes 6 blends that meet the criteria during strain gauge testing in December 2014

Until a long term solution other than the pressure plate is installed into the machine and the turbine is appropriately equipped with strain gauge and blade vibration monitoring hardware, Duke will not fully understand the total impact of this thermal energy on the blades. Duke Engineering believes that the brief telemetry testing period conducted in December 2014 does not – by itself – provide conclusive enough evidence to support (or refute) this contributing factor of thermal distress, as not all blend conditions and configurations were exercised during the testing period

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Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

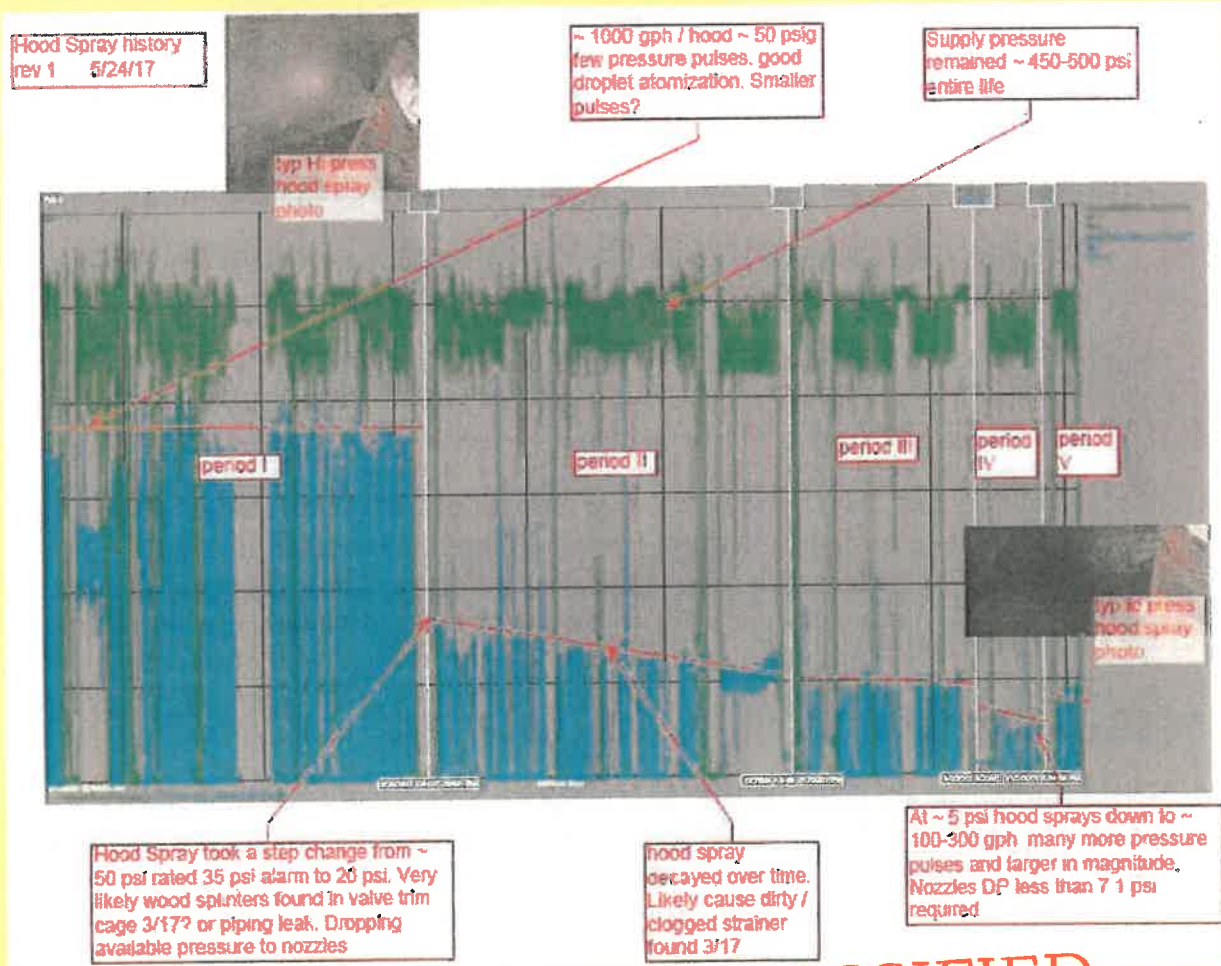
During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the hood sprays control valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the same control valve had filled with debris in prior years' operating.

Figure 2, below, demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization through centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

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Figure 2 -- Hood Spray Pressure Degradation Over Periods 1-5



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Zone Analysis – Shroud Fretting Fatigue

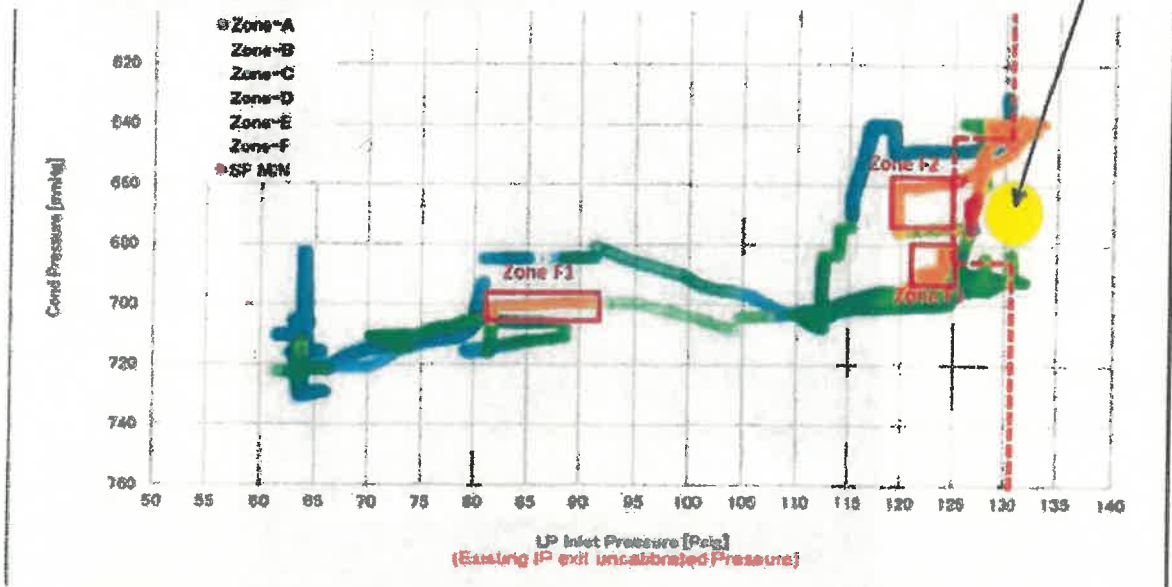
Based on data from the Period 3 blade strain gauge test in December 2014, the OEM identified areas (referred to as “Zones”) where blade response was high, but still below the OEM design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1, Zone F2, and Zone F3 (shown by the red rectangles in Figure 3, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period. The OEM did not provide any restriction(s) to operation in Zone F1, Zone F2, and/or Zone F3 – only restrictions relative to “operation in the avoidance zone” identified by the area of the graph to the right of the dotted red line in Figure 3.

Figure 3 -- Data Presented by MHPS During a Presentation Dated 15 March 2017

Damage Mechanism

Blade Response – Design Margin
Example : Shroud Fretting Fatigue

Unable to test due to excessive blade response



- Blade response is evaluated through the integration of the stress response all the modes between 180Hz to 120Hz

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

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Table 2 -- Time (In Hours) Spent in Each Zone and the Total Compared with Operating Time

	Time in Zone				Total Turbine Operating Hours	% Time in Zone F
	F1	F2	F3	Total		
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

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The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure 4. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

Figure 4 -- Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear



Period 5 did have high energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending as compared to operating hours in Zone F1.

Loss of Dampening -- Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

HVOF hard-facing can reduce the amount of base material fretting during operation and is used on many applications across the industry for blading contact surfaces. When applied, the HVOF hard-facing changes the frictional forces of the contact surface reducing fretting and has an increased hardness to prevent material loss.

The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers,

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which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting stress location became the blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward potential blade failure will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the RCA investigation between Periods 3 and 4, technical questions arose relative to “as left” blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren’t both taken into consideration together, then as the blades began to “untwist” as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture “worst case” geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

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Appendix A: Bartow L-0 Event Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW (Nameplate)	420 MW	450 MW	450 MW	390 MW
Operating Restrictions	None – MHPS Intent Was to Follow Heat Balance Diagrams.	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111 psig Limit on IP Exhaust
Blade Overspeed Condition	Overspeed Testing in MFG		Overspeed Tested in Japan	No Overspeed Testing	No Overspeed Testing
Avoidance Zone Exceedance	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,284 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) and to continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).	Not a forced outage – Outage planned to upgrade to "heavy duty" blades. Some blade damage (e.g. chipping at contact corners) was observed from removed service blades. Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.	During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits – unit ran in zone for <20 hrs. No blade cracking observed after testing (when the test instrumentation removed).	Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil. Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events. Jan 2017 "loss of mass" event – blade fragment projectile traveled through the LP turbine rupture disk diaphragm. Dental mold impression of failure surfaces indicate ~10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).
Information Shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.

Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	Different Radial Height Relative to Bartow L-0 (About 1")
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	No HVOF
Blade design	Original	Original	Original	Attack Angle Change
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

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Appendix C: Empirical Data Supporting Root Cause

Empirical Support for Root Cause

		Excessive Steam Flow			
Period	Operating Hours	Driving Mechanism Present	Avoidance Zone Exceedance Hours	Exceedance Hours / (1k Operating Hours)	Normalized Ranking
1	21,734	X	2,466	0.11	1.00
2	21,284		1	0.00	0.00
3	10,286	X	240	0.02	0.21
4*	2,942		1	0.00	0.00
5	1,561		0	0.00	0.00

		Thermal Distress ($\Delta T_{10}/dt$)			
Period	Operating Hours	Driving Mechanism Present	Counts ($\Delta T > 20 \text{ deg. F}_{10} / \text{Minute}$)	Counts / (1k Operating Hours)	Normalized Ranking
1	21,734	X	15	0.60	0.17
2	21,284	X	7	0.33	0.00
3	10,286	X	57	5.60	0.33
4*	2,942	X	3	1.02	0.28
5	1,561	X	5	3.20	0.00

		Pressure Pulses				
Period	Operating Hours	Driving Mechanism Present	Avg. Hood Spray Pressure (psig)	Hours of Hood Spray Operation	% of Total Operating Hours	Normalized Ranking
1	21,734	X	85.2	5,098	23	0.68
2	21,284	X	18.2	7,548	34	0.80
3	10,286	X	10.4	440	4	0.00
4*	2,942	X	5.5	174	6	0.17
5	1,561	X	8.7	98	6	0.17

		Loss of Dampening
Period	Operating Hours	Driving Mechanism Present
1	21,734	N/A
2	21,284	N/A
3	10,286	N/A**
4*	2,942	X
5	1,561	N/A

Period 1	Jun 2009 to Mar 2012
Period 2	Apr 2012 to Aug 2014
Period 3	Dec 2014 to Apr 2016
Period 4	Jun 2016 to Oct 2016
Period 5	Dec 2016 to Feb 2017

General Notes

For Period 4, the first L-0 blade tip was lost on 7/6/16 at about 10:50AM -- BEFORE the thermal event on 7/16/16 and BEFORE operation above "avoidance zone" limit on 08/01 - 9/25/16 (55 min total).

"Excessive Steam Flow" Notes

"Avoidance Zone Exceedance Hours" -- Measured number of operating hours in exceedance of 15,000 lb/hr-ft² limit as indicated by the IP exhaust pressure

"Exceedance Hours / (1k Operating Hours)" -- Number of exceedance hours per 1000 hours of operation in a given period
 "Normalized Ranking" -- Data normalized against the highest value in Column F

"Thermal Distress ($\Delta T_{10}/dt$)" Notes

"Counts ($\Delta T > 20 \text{ deg. F}_{10} / \text{Minute}$)" -- "Counts" are defined as the number of measurable blends where there was a slope change (+/-) greater than (20 degrees superheat / min) at the hood spray thermocouples -- Data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW

"Counts / (1k Operating Hours)" -- Number of "counts" per 1000 hours of operation in a given period
 "Normalized Ranking" -- Data normalized against the highest value in Column F

"Pressure Pulses" Notes

"Avg. Hood Spray Pressure (psig)" -- Calculated from PI Historian data (???) -- Verify)

"Hours of Hood Spray Operation" -- "Hours of Hood Spray Operation" is a weighted value -- There is a 1.00 multiplier at 50 psig varying linearly to a 1.75 multiplier at 8 psig

"% of Total Operating Hours" -- The "weighted" hours of hood spray operation divided by the total number of operating hours -- converted to a percentage value
 "Normalized Ranking" -- Data normalized against the highest percentage value in Column G

"Loss of Dampening" Notes

** For Period 3, there was hard-facing on the Mid-span Scrubber ONLY -- Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was likely due to loss of dampening at the scrubbers, which were HVOF-coated -- The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion

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Appendix D: Reference Materials

Mitsubishi RCA Presentation(s) – 22 September 2017 and 02 October 2017

MHPS's evaluation is based on the data captured between Period 2 and 3 during blade telemetry testing. MHPS's evaluation is extensive and has allowed us to identify and evaluate contributing factors. MHPS's intent was to draw conclusions based on actual data collected. The telemetry testing window was short, and not all operating conditions were witnessed during the testing (steady state and transient events). Because of this the conclusions from this report may not be all encompassing of the drivers and conditions that are causing the blade failures.



Bartow RCA
Customer 9-22-17.pdf



Bartow RCA
Customer 10-2-17.pdf

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Executive Summary

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Over the past 3 plus years, Duke Energy Florida LLC (Duke), at times working independently and at times together with Mitsubishi Hitachi Power Systems (MHPS), undertook a root cause analysis (RCA) of the cause(s) for the Unit 4S L-0 blade cracks and failures that occurred during normal station operations at Bartow Station. The intervals between failures had become shorter after each failure despite MHPS's attempts to improve the blades' performance and the station's adherence to the revised OEM operating instructions received after each successive failure.

Only after the telemetry test was completed and after the onset of Period 3, in approximately March 2015, (as a result of the telemetry test) did MHPS create an "avoidance zone" in which the station was not to operate except as needed to ramp up or down. Bartow operated in the avoidance zone only 1.15 hours in Period 4 and 0 hours in Period 5, but suffered two (2) further failures in successively shorter periods. Thus, after the fifth failure, Duke concluded that operation in MHPS' designated avoidance zone did not explain the failures and looked at whether other factors potentially were related or contributed to the failures.

Duke considered both operational and design aspects. With respect to operational factors, the Duke team used the Plant Information ("PI") data historian and operational data from each period and retroactively calculated¹ whether those factors had any correlation to the failures. Potential factors in the operational category included:

- Operations in MHPS Avoidance Zone -- Low Pressure (LP) Turbine "Excessive" Steam Flow
- Bartow Blending Operations -- Potential Thermal Distress (Rate of Change in Super Heat Over Time, dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)

Duke Engineering concluded that there was no correlation between any one of the above-listed factors and the five (5) failure periods. Notably, Duke was only able to study each factor independently based on available data. In the absence of (1) blade telemetry, (2) duplication of the factors in various combinations, and (3) operation in varying but normal conditions, it is not possible to study how each factor relates to and interacts with any other factor, if at all.

Duke also studied design factors unique to MHPS 40" steel blades. This aspect of the RCA was largely deductive because MHPS controls design data, although MHPS did provide FEA stress and frequency analyses, material properties, and some dimensional information. The following factors were included in this portion of the study:

- Zone Analysis -- Shroud Fretting Fatigue

¹ Because MHPS's operational constraint called the Avoidance Zone was not provided by MHPS until after the onset of Period 3, one could only look at hours in that zone after-the-fact for Periods 1 and 2.

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- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

With regard to the “Hard-Facing on Mid-Span Snubbers” factor, Duke was able to conclude and MHPS concurred, that this factor played a part in the blade failure in Periods 3 and 4. With respect to the Zone Analysis and Blade Fitment factor, although MHPS made no concession, it is currently re-engineering its 40” blades and making changes to the blades’ geometry as discussed by MHPS Engineering in a 22 September 2017 presentation made to Duke.

Based on its observations and study, Duke has been and remains of the opinion that the root cause of the failures in the ST L-0 40” blades is the blade design/lack of blade design margin. That is to say, under expected operating conditions at Bartow’s 4x1 Combined Cycle (CC) Unit, the MHPS blades are substantially more fragile than similar 40” blades both in Duke’s CC fleet and elsewhere in the industry.²

Duke’s conclusion is based on its study of the events and information that includes data supplied by MHPS, PI data from Bartow, information from similar units in Duke’s fleet, and industry experience with the 40” blades. MHPS did not provide proprietary information concerning engineering and testing of the 40” blades but did provide engineering assistance and strain gauge data from a brief period of MHPS-led telemetry testing during December 2014. Duke provided all operational information requested by MHPS and met with MHPS multiple times to discuss both MHPS’ findings and Duke’s independent research and findings. This RCA report is Duke’s product and presents its view of the root cause based on all inputs received.

For Bartow, the long-term solution is to replace the L-0 blades with blades of a different design and/or to retrofit the LP steam path and/or continue operation with pressure plate.

With either a redesign of the MHPS 40” blades or replacement with blades of a different make or an LP steam path retrofit, telemetry instrumentation and blade vibration monitoring are necessary to ensure that all potential upset conditions are resolved.

Historical Overview

Bartow is a 4x1 CC Station with a steam turbine (ST) manufactured by MHPS. The ST was purchased from Tenaska Power Equipment, LLC (Tenaska) which intended to use it for a 3x1 CC with a gross output of 420MW. The ST was never delivered to Tenaska and remained with MHPS in a warehouse in Japan until Duke purchased the unit in 2006.

Before the ST was purchased by Duke, Duke contracted with MHPS to evaluate the ST design conditions and to update heat balances for a 4x1 CC configuration. MHPS updated the heat balances for use in a 4x1 CC configuration. CC units blend steam from the combustion turbines (CT) as they start-up and/or

² The most commonly reported issue with the 40” L-0 blade design elsewhere is water erosion, which both Duke and MHPS agree is not a contributing factor to the Bartow failures.

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shut-down with steam to the ST. These blending events, which are a common occurrence for CC units, result in brief periods of higher steam temperatures and flows into the condenser near the ST L-0 blades.

Since commissioning of the Bartow ST in 2009, there have been five (5) events involving L-0 blade failures and/or replacements as described, below.

Each 40" MHPS steel blade is twisted with a "root end" that connects it to the hub, a snubber at the mid-point or mid-span, and a shroud with airfoil tips at the top. While the ST spins up to its operating speed of 3600rpm, each blade elongates and starts to untwist. The snubbers and airfoil tips are designed to contact each other and create a stabilizing central and outer ring. If a snubber or airfoil tip fails, the blades can vibrate excessively and can cause sudden catastrophic failure. Although none of the five (5) Periods at Bartow involved a complete blade loss or catastrophic failure, two (2) involved upsets and each event affected mid-span snubbers, shroud Z-Locks, and airfoil tips.

The five (5) Periods are summarized in Table A. Each Period's start date is when the ST was put into service and each end date reflects either when the ST was taken off-line or suffered an unplanned outage. The blades for each period are described by "Type." The ST was sold and during Period 1 was operated with Type 1 blades, which at MHPS' recommendation and urging were replaced – turbine end (TE) blades only – with a re-engineered Type 1 blade at the start of Period 2. Period 2 ended with a planned shut-down, during which the TE and generator end (GE) blades were replaced with an OEM-improved design (Type 3) even though the in-service Type 1 L-0 blade condition was such that they could have run longer. The Type 3(v1) blades had hard-facing on the mid-span snubber contact surfaces and MHPS ran its brief period of telemetry testing. Damage found at the end of Period 3 resulted in a forced outage and the installation of new Type 3(v2) blades with hard-facing on the mid-span snubber, as well as hard-facing now added to the Z-Lock contact surfaces. When these Type 3(v2) blades failed at the end of Period 4, they were replaced with the original Type 1 blades for Period 5. When these Type 1 blades failed at the end of Period 5, the L-0 blades were replaced with a pressure plate.

MHPS provided OEM operating parameters in each Period as reflected in Table A under the heading "MHPS IP Exhaust Pressure Operating Limits." For Period 1, these limits were the design limits that accompanied the ST at purchase. After the damage was discovered at the end of Period 1, MHPS imposed a lower IP exhaust pressure limit. In Period 3, when the Type 3 blades were installed, MHPS raised the limit, in accordance with the original proposal by MHPS to supply blades for Period 3 that would allow operation up to 450 MW but also stay within the limits established as a result of the telemetry test. After the telemetry test, MHPS sent out a chart it called the "Avoidance Zone" and suggested that blade damage would be avoided if Duke operated as few hours as possible in the zone. The practical result of the avoidance zone limits meant that the Bartow ST unit could not achieve 450 MW as the IP exhaust pressure was, and to this day still is, limited when condenser pressure is in a range the unit normally must run in. In Period 4, with the discovery of additional damage, MHPS lowered its IP exhaust pressure limit and did so again in Period 5.

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Table A: Bartow L-O Events Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	June 2009 to March 2012	April 2012 to August 2014	December 2014 to April 2016	May 2016 to Oct 2016	December 2016 to February 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-O Blade Configuration	Type 1	Type 1 (re-engineered)	Type 3 (v1)	Type 3 (v2)	Type 1
MHPS Expected ST Output	420 MW (Nameplate)	420 MW	450 MW ³	450 MW ³	390 MW
MHPS IP Exhaust Pressure Operating Limits	Machine controlled to HP, IP and Condenser design limits	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111.5 psig Limit on IP Exhaust
Retroactive Calculation of Avoidance Zone "Exceedance" based on the MHPS Period 3 Avoidance Zone chart ⁴	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,284 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period	<p>Planned outage for valve work, as well as annual L-O inspections.</p> <p>At the start of this period, MHPS approved 4x1 (unfired) operations at 392 MW output, as well as 3x1 (duct fired) operation at 420 MW, supported by MHPS-provided heat balance documentation.</p> <p>During a plant shut down a visual inspection of the ST L-O blades revealed damage to the turbine end blade snubbers.</p>	<p>Planned outage for upgrade to "heavy duty" blades, based on MHPS representation that it had improved design.</p> <p>Some blade damage (e.g. chipping at contact corners) was observed from removed service blades.</p>	<p>Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.</p> <p>During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits – unit ran in zone for <20 hrs.</p> <p>Planned outage for valve work, as well as an annual L-O inspection.</p> <p>No blade cracking observed after testing (when the test instrumentation removed).</p> <p>Stellite hard-facing added to snubbers only.</p>	<p>Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.</p> <p>Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil.</p> <p>Stellite hard-facing added to the blade Z-Lock.</p>	<p>Jan 2017 "loss of mass" event – blade fragment projectile traveled through the IP turbine rupture disk diaphragm.</p> <p>Dental mold impression of failure surfaces indicate ~10⁶ striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).</p> <p>L-O blades removed and pressure plate installed; pressure plate restricted ST output to between 360-380 MW. MHPS maintains operational restrictions on ST.</p>
Information Shared with MHPS	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.

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³ Outside of operation in the MHPS Avoidance Zone

⁴ For purposes of comparison, the Duke RCA team looked at hours in the Avoidance Zone even for periods in which that concept had not been introduced.

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Operational Factors Potentially Impacting MHPS Blades

Low Pressure (LP) Turbine Excessive Steam Flow – “Running in the Avoidance Zone”

After the Period 3 outage was concluded and the ST was back in service, MHPS offered a view that high back-end loading on the LP turbine last stage blades must have been a significant contributing factor to the past L-0 blade damage/failures. Back-end loading is created by steam flow and operating pressure through a turbine section. Based on hindsight, MHPS Engineering claimed that at the time of the first failure (Period 1), Bartow Unit 4S exceeded the back-end loading limitation of 15,000 lb/hr-ft² by many hours and that the MHPS 40” L-0 fleet average for back-end loading was closer to 12,000 lb/hr-ft². Although MHPS had not previously imposed a back-end loading limitation, it then created what it called the “Avoidance Zone” and suggested longer run times in the avoidance zone were the root cause of the first three failures.⁵

Then and now, Duke Engineering does not agree that back-end loading above 15,000 lb/hr-ft² has been the failure-driving mechanism for the documented L-0 events. As Table A illustrates, Periods 2, 4 and 5 saw operating hours in the MHPS defined “Avoidance Zone” of only 1 hour, 1.15 hours and 0 hours, respectively, and still Bartow suffered damaged blades. Period 3 had only 240 hours in the avoidance zone, less than 2% of its total operating hours. Furthermore, by a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the “avoidance zone” – 2,466 out of 21,734 total hours – but despite the greatest number of hours, blade damage in this Period was limited to five (5) broken mid-span snubbers on the TE of the machine and a lesser degree of fretting on the shroud Z-Lock contact surfaces for both TE and generator end (GE) of the machine than seen in other Periods. The next highest period in the avoidance zone, Period 3, with 240 hours (out of 10,286 total hours – (11 hours of which were during approved instrumented blade telemetry tests performed by MHPS in December 2014), showed significantly greater amounts of blade damage and fretting to the Z-Lock contact surfaces on both ends of the machine than Period 1.

While the amount of Z-Lock wear cannot be quantified for Periods 1 and 3, photographs show the difference (See Figure 1 below).

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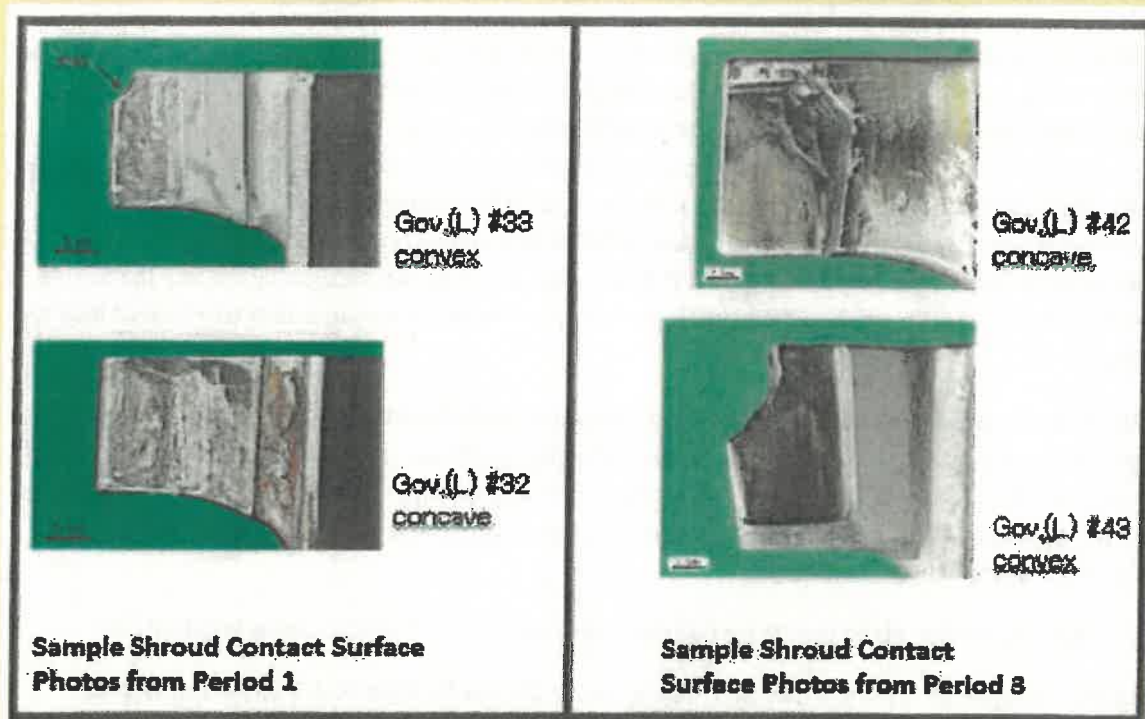
⁵ MHPS Engineering extrapolated the December 2014 data to isolate operation in the Avoidance Zone as the root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil as seen during Periods 1-5. Duke Engineering does not agree that this data can be extrapolated over all five Periods, in part, because the data does not include normal operating conditions at Bartow and in part, because the information does not explain what occurred in each Period. Without telemetry over a sufficiently long period, under a sufficiently normal set of operating conditions after new blades and/or other equipment is installed, the December 2014 data yields no reliable RCA conclusions.

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Figure 1 –Photos of Shroud Contact Surface Wear for Periods 1 and 3



Based on comparative run times and damage, it is difficult to conclude that the L-0 blade damage in each Period or any particular Period is due to unit operation in the avoidance zone.⁶

Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust – “Blending Operations”

After the Period 5 failure, which occurred with zero hours in the avoidance zone and with no other explanation offered by MHPS, the Duke RCA team began to consider whether other operational aspects might impact exhaust conditions of the LP. The Duke team looked for other mechanisms that might introduce forces great enough to initiate cracks in snubbers including Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF). The two (2) operational conditions that might conceivably produce forces great enough to initiate snubber cracks are blending and the use of hood sprays (especially with low out-of-spec inlet pressure). Blending is discussed first.

Since the design of the condenser includes spargers (or “dump tubes”) for the hot reheat (HRH) and LP bypass steam flows from each of the four (4) CTs, and since thermocouples positioned at the LP exhaust

⁶ Even though the L-0 blades are no longer in the ST and a pressure plate has been installed, MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current IP Turbine exhaust pressure operating limits because of “potential impacts to upstream blading” – i.e. the L-1 blade sets. This suggests that MHPS is unsure what effect if any is created by its “avoidance zone” and more importantly points to a design flaw that may affect more than the L-0 blades.

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just downstream of the L-0 blades (i.e. hood spray thermocouples) have experienced significant changes in temperature during a blend operation, Duke reviewed these blend operations.

Using Excel and PI Datalink, Duke Engineering determined which operational blending events might have affected the L-0 blades in order to isolate those higher risk events from the large quantity of blending operation of data for Periods 1-5. Duke identified blends with a slope change greater than 20° superheat/minute at the hood spray thermocouples and with an ST output greater than 50 MW. Duke Engineering selected the 20° F change in superheat and 50 MW minimum output as proxies for conditions when blend steam had high or low enthalpy (LCF and HCF) as reflected by high thermocouple temperature/superheat rate of change.⁷ While this measure does not necessarily indicate the overall severity of any loadings on the L-0 blades, it serves as a proxy for reviewing events which could load the blades.

Operationally, blends are not defined or constrained to strict parameters because of the number of variables that can affect blends. High and low enthalpies therefore, are not functions that are typically monitored by an alarm or otherwise. This study of blends was done solely with the benefit of hindsight for this RCA. In studying blends at Bartow, the Duke team also looked at blends at other stations and found similar high and low enthalpies.

The following are the blend counts for Bartow in each Period based on the above-listed criteria:

Table B – Number of “Counts” that Meet the Blending Criteria for Periods 1-5 on Bartow Unit 4S.

	Number of Operating Hours in Each Period	Number of Blends (or “Counts”) Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

*Includes 6 blends during strain gauge testing in December 2014

Using the same criteria as used for Bartow, blending operations at the HF Lee CC plant and for Hines Energy Power Block 2, which have 40” and 42” L-0 blades, respectively (but from different OEMs than MHPS), were used as a basis of comparison to Bartow – see Table C.

Table C – Number of “Counts” that Meet the Blending Criteria on the HF Lee CC ST

Duke Station	Date Range	Number of Operating Hours	Number of Blends (or “Counts”) Meeting Criteria
HF Lee CC ST	01/01/2014 to 01/01/2016	15,045	22
Hines PB2 ST	09/01/2015 to 09/01/2017	16,123	44

⁷ Although Duke could have used smaller temperature changes, selecting small changes (e.g. a three- or five- degree difference) would yield too many results, most of which could not cause a LCF or HCF effect. Likewise, at too-high a temperature delta, too many data points may have been eliminated.

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Given the comparison with Lee and Hines CC STs and the variability in blending events in the Bartow Periods, Duke was unable to draw any correlation between blending and the impacts on the MHPS blades. Bartow, Hines and Lee are similar in their blending rates and blending counts and yet, Lee's and Hines' blades have never been impacted like what has been seen at Bartow. This reinforces the Duke team's conclusion that the Bartow failures are attributable to the design or slim design margins in the MHPS 40" blades.

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke team also studied whether hood spray operations were a possible cause of high and low energy forces on the L-0 blades because of the proximity of the sprays to the L-0 blades. The hood spray nozzles rely on pressure drop across the nozzle to create a vortex inside the nozzle that causes atomization of the water through centripetal force. Reduced pressure drop corresponds with a reduction in atomization and lower hood spray atomization may create dynamic pressures affecting the L-0 blades, as large water droplets evaporate/flash-off in the exhaust stream creating pressure pulses.

The hood spray operation is programmed into the Ovation DCS control system and is automated with no operator interaction. The condensate pump output acts as a source of water for the spray. A control valve reduces the roughly 500 psig condensate pressure to the spray design pressure of 50 psig. A review of the OEM-provided instructions directs use of hood sprays during the following two conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160° F

Although not clear why, the Bartow hood spray data shows that the hood spray had been programmed during unit construction to operate any time blending takes place – similar to curtain sprays. Duke is not able to determine who programmed the hood spray in this way; MHPS would have had input in the control system, but the architect/engineer typically designs the plant-wide control system.

In any case, because of the manner it was programmed, the hood spray operations occurred at greater rates than would have normally occurred. Two questions are raised in hood spray operations: (1) are the temperatures at the hood spray thermocouples normal or excessive and (2) is the hood spray pressure normal?

Hood spray thermocouple data shows the hood sprays rarely reached 160° F during normal operation and never exceeded 165° F. Higher temperatures are sometimes seen after a shutdown or unit trip as exhaust pressure increases, most likely due to the hot LP casings and some windage. During shutdowns and/or unit trips, there were no temperature readings above 201° F (one very brief reading of 1040° F was the result of an instrumentation issue).

Having eliminated excessive LP exhaust temperature as a concern, the team looked at hood spray pressure and found it had steadily decreased over successive Periods likely due to clogged sprays.

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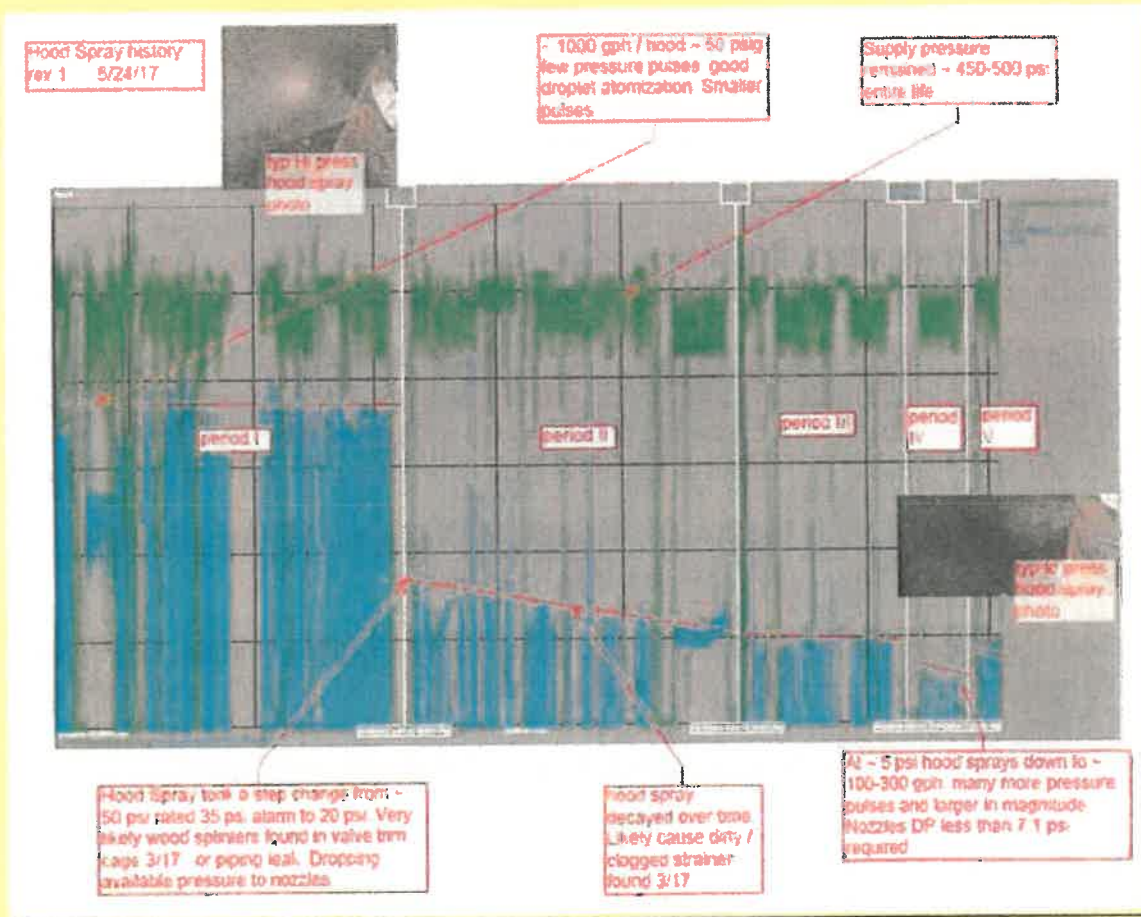
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Figure 2 depicts the pressure decrease in the hood sprays over time. The decline in water pressure at the hood spray nozzles, likely caused by debris in the valve trim, results in reduced atomization.

At the kind of hood spray pressures shown in Figure 2, the atomization of the hood sprays would have been poor. Larger water droplets will cause pressure pulses as evaporation occurs, during times when the LP exhaust steam temperatures are elevated during blending.

Figure 2 – Hood Spray Pressure Degradation Over Periods 1-5



Control of the hood sprays is automated within the plant-wide control system and not controlled by the operators. After a plant is commissioned, the hood sprays are not normally checked for accuracy and again, until there had been successive failures, there was no reason to focus on the hood spray system's functionality. Although the review that was conducted after the 5th failure revealed lower pressure which may have contributed to some additional wear of the blades, the Duke team does not believe this is the root cause of the failures as the design of the blades should have been robust enough to withstand some increased pressure pulses. Further, MHPS does not believe that any pressure pulses from the hood spray would have been strong enough to harm blades.

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Zone Analysis – Shroud Fretting Fatigue

Based on data from the blade strain gauge telemetry test in December 2014, MHPS identified areas (referred to as “zones”)⁸ where blade response was high, but still below the OEM design limit, occurring during the normal operation range of the LP turbine (See Figure 3). These zones were neither something Duke was told about nor the result of any operational factors. They simply reflect how MHPS’ 40” blades function at certain operating conditions. Notably, MHPS never issued an operational restriction associated with these zones.

As part of its RCA after the fifth and most recent failure, the Duke Engineering team reviewed the time of operation in these MHPS-identified zones in an effort to determine whether there might be some correlation between the zone time and failure. Duke Engineering was interested in this issue because of the observed excessive Z-Lock wear in Period 5 that occurred after a short operation time. Excessive wear at these contact surfaces is a sign of excessive blade movement during operation. Since there was no operation in Period 5 above the IP turbine exhaust pressure limit “avoidance zone” designated by MHPS, the only other possible reason for the wear is higher dynamic stimulus (Zone F as identified by the telemetry test).

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Zone	Time	Response	Design Limit	Notes
A	10:00-10:05	High	Below	Normal
B	10:05-10:10	High	Below	Normal
C	10:10-10:15	High	Below	Normal
D	10:15-10:20	High	Below	Normal
E	10:20-10:25	High	Below	Normal
F	10:25-10:30	High	Below	Normal
G	10:30-10:35	High	Below	Normal
H	10:35-10:40	High	Below	Normal
I	10:40-10:45	High	Below	Normal
J	10:45-10:50	High	Below	Normal
K	10:50-10:55	High	Below	Normal
L	10:55-11:00	High	Below	Normal

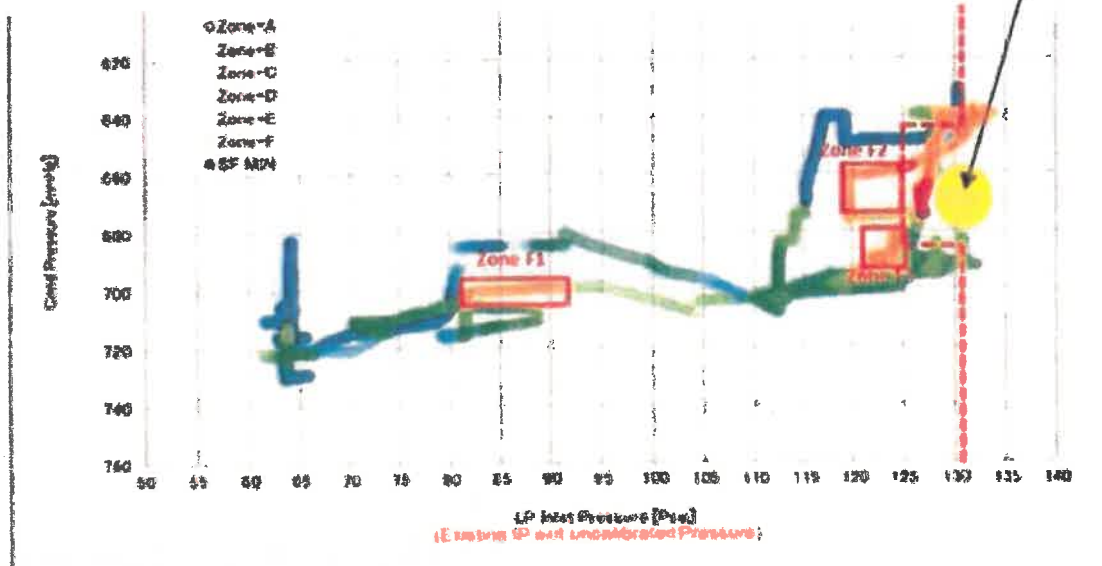
⁸ These zones are not MHPS operational constraints and differ from the Avoidance Zone discussed above.

Figure 3 – Data Presented by MHPS During a Presentation Dated 15 March 2017

Damage Mechanism

Blade Response – Design Margin Example : Shroud Fretting Fatigue

Unable to test due to excessive blade response



- Blade response is evaluated through the integration of the stress response all the modes between 180Hz to 120Hz

Table D shows the time in hours in each of the three (3) zones identified during the telemetry test for each Period. The total time in the three (3) zones compared with the total operating time is reflected as a percentage.

Table D – Time (in Hours) in Each Zone and Compared with Operating Time

	Time in Zone				Total Turbine Operating Hours	% Time in Zone F
	F1	F2	F3	Total		
Period 1	901.2	466.2	9.7	1377.0	21734	6.3%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

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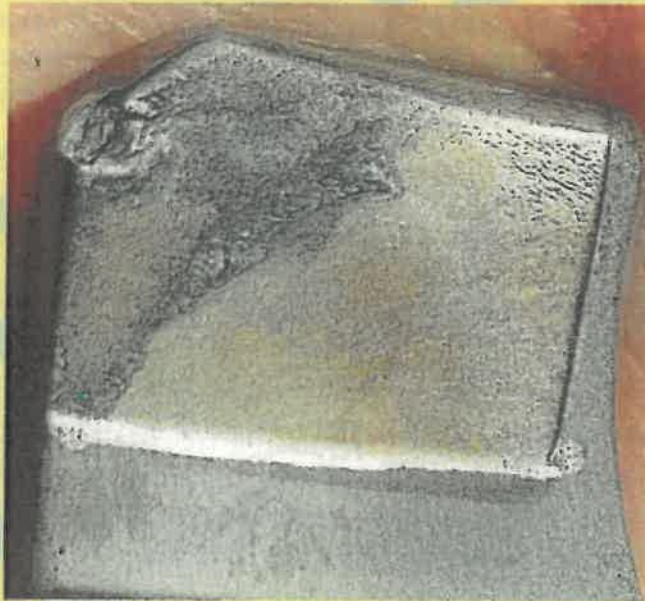
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Figure 4 shows the wear on one of the Period 5 Z-Locks. While varying degrees of wear are seen on the Period 5 Z-Locks, the wear is higher than what one would expect given the relatively low total turbine operating hours. Period 5's time in blend mode was consistent with those in other Periods and does not explain the amount of wear.

While the findings are not completely conclusive, there is good reason to believe that MHPS' design may be susceptible to damage when run in these zones. All Periods had hours in Zone F1 and F2. In addition, both on a percentage and absolute basis, Period 5 had a significant number of operating hours in this higher dynamic stress zone. Because each Period included run times in one or more zones and because each Period resulted in differing degrees of damage without direct correlation to the run times in those zones, it is difficult to conclude that operation within the zones is the cause of the L-O blade failures. However, if the design margin on the blades is small, the blades may be susceptible to cracking, excessive wear, etc., when the unit either runs in or passes through these zones.

Figure 4 – Photo of an L-O blade Z-Lock from Period 5 Showing Contact Surface Wear



Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

High Velocity Oxygen Fuel (HVOF) hard-facing can reduce the amount of base material fretting (wear) during operations and has many applications for blading contact surfaces in the industry. HVOF hard-facing can also change the frictional forces of the contact surface by reducing the coefficient of friction. However, as frictional forces are reduced, so are the dampening forces derived from them. A reduction in dampening, in most cases, means an increase in dynamic forces and motion.

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Duke Engineering considered whether dampening loss may have been a contributing factor during Periods 3 and 4, when MHPS provided HVOC hard-faced coating on certain parts of the blades. In Period 3, only the mid-span snubbers had hard-facing. As a result, the shroud Z-Lock contact surfaces had more damage relative to other Periods, likely due to a loss of dampening at the snubbers. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

In Period 4, both the mid-span snubbers and the shroud Z-Lock contact surfaces had hard-face coating. Given that both the mid-span and shroud contact surfaces were HVOF-coated, the limiting factor then became the blade airfoil high stress location in the trailing edge, which was the observed failure at the end of Period 4. In discussions with MHPS, MHPS agreed that its attempt to harden the blade contact surfaces likely contributed to the failures in Periods 3 and 4.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

To understand this issue, recall that at high speeds the Z-Lock and snubbers act as the mechanism by which the 40" blades are prevented from untwisting completely and moving loosely. Thus, the distance between Z-Locks and between snubbers must be precisely engineered to account for expansion and movement between the blades during operation. If the blades are too tight, (initial clearances too small) there will be too much force at the contact surface raising stresses and make breakage more likely, and if too loose (initial clearances too large), there will be too little force to provide proper dampening or allow blade vibration frequency and modes to change, potentially leading to failure.

Between Periods 3 and 4, Duke raised technical questions relative to "as left" blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. These questions were concerned with whether blade gaps at both points should be viewed together.

Because MHPS installed telemetry and conducted strain gauge testing for a short period in December 2014 at the beginning of Period 3, the Type 3(v1) L-0 blades were used to establish a baseline blade response to capture "worst case" geometry variations.

MHPS concluded that the dimensional tolerance between the Type 3(v1/v2) blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 blade (Periods 3 and 4) showed greater distortion than the Type 1 blade (Periods 1, 2 and 5).⁹ With a greater geometry variation, the Type 3 blade provided less mechanical dampening (relative to the Type 1 blade) because of the smaller contact area and misalignment.

While MHPS contends that geometry variation on the Type 3 blade is not significant enough to have negatively impacted blade stress/response, MHPS also implicitly acknowledges that blade fitment/geometry is important in its current efforts to redesign the 40" blade following the fifth failure. In fact, it is changing the geometry in response to specific Duke suggestions.

In conclusion, Duke Engineering believes that the "as-left" placement of the blades in the 3rd and 4th Periods had some impact on the failures, though again, had the blades been more robust, they may not

⁹ These findings are consistent with an independent analysis of the blades by Duke using third party scanning.

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have failed to the extent seen in those Periods. MHPS bears the responsibility for this cause as the replacement Services were entirely in its control.

CONCLUSION:

Based on its observations and study, Duke has been and remains of the opinion that the root cause of the failures in the ST L-0 40" blades is the blade design/lack of blade design margin. That is to say, under expected operating conditions at Bartow's 4x1 Combined Cycle (CC) Unit, the MHPS blades are substantially more fragile than similar 40" blades both in Duke's CC fleet and elsewhere in the industry.¹⁰

Duke's conclusion is based on its study of the failure events and both design and operational information including data supplied by MHPS, PI data from Bartow, information from similar units in Duke's fleet, and industry experience with the 40" blades. MHPS did not provide proprietary information concerning engineering and testing of the 40" blades but did provide engineering assistance and strain gauge data from a brief period of MHPS-led telemetry testing during December 2014. Duke provided all operational information requested by MHPS and met with MHPS multiple times to discuss both MHPS' findings and Duke's independent research and findings. This RCA report is Duke's product and presents its view of the root cause based on all inputs received.

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¹⁰ The most commonly reported issue with the 40" L-0 blade design elsewhere is water erosion, which both Duke and MHPS agree is not a contributing factor to the Bartow failures.

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Appendix A: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	<i>Different Radial Height Relative to Bartow L-0 (About 1")</i>
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	No HVOF
Blade design	Original	Original	Original	<i>Attack Angle Change</i>
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

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Appendix B: Empirical Data Concerning Factors which May Have Affected L-0 Blades

Empirical Support for Root Cause

Period	Operating Hours	Excessive Steam Flow			
		Potential Factor Present	Auxiliary Zone Steam Hours	Shutdown Hours / (1k Operating Hours)	Normalized Ranking
1	21,794	X	1,459	0.11	0.07
2	21,284		3	0.00	0.00
3	10,385	X	240	0.02	0.17
4	2,842		1	0.00	0.00
5	1,581		0	0.00	0.00

Period	Operating Hours	Thermal Disturbance (dT _{max} /dt)			
		Potential Factor Present	Counts (ΔT > 20 deg_Fm / MinSec)	Counts / (1k Operating Hours)	Normalized Ranking
1	21,794	X	13	0.00	0.00
2	21,284	X	7	0.00	0.00
3	10,385	X	87	0.00	0.00
4	2,842	X	3	1.00	0.00
5	1,581	X	5	1.20	0.00

Period	Operating Hours	Pressure Fluctuation				
		Potential Factor Present	Avg. Hood Spray Pressure (psig)	Hours of Hood Spray Operation	% of Total Operating Hours	Normalized Ranking
1	21,794	X	35.2	1,886	2.4	0.07
2	21,284	X	13.2	7,442	34	0.00
3	10,385	X	10.6	460	4	0.00
4	2,842	X	5.5	174	6	0.17
5	1,581	X	6.7	33	0	0.00

Period	Operating Hours	Loss of Dampening
		Potential Factor Present
1	21,794	N/A
2	21,284	N/A
3	10,385	N/A
4	2,842	X
5	1,581	N/A

Period	Operating Hours	Blade Fitment	
		Potential Factor Present	Normalized Ranking
1	21,794	X	0.00
2	21,284	X	0.00
3	10,385	X	0.00
4	2,842	X	0.00
5	1,581	X	0.00

Period 1 Jun 2009 to Mar 2011
 Period 2 Apr 2012 to Aug 2014
 Period 3 Dec 2014 to Apr 2016
 Period 4 May 2016 to Oct 2016
 Period 5 Dec 2016 to Feb 2017

"Excessive Steam Flow" Notes

"Auxiliary Zone Exceedance Hours" -- Measures number of operating hours in exceedance of 15,000 lb/hr-ft² limits as indicated by the PI exhaust pressure

"Shutdown Hours / (1k Operating Hours)" -- Number of shutdown hours per 1000 hours of operation in a given period

"Normalized Ranking" -- Data normalized against the highest value in the column, "Shutdown Hours / (1k Operating Hours)"

"Thermal Disturbance (dT_{max}/dt)" Notes

"Counts (ΔT > 20 deg_Fm / MinSec)" -- "Counts" are defined as the number of measurable blades where there was a slope change (°/s) greater than (20 degrees superheat / min) at the hood spray thermocouples -- Data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW

"Counts / (1k Operating Hours)" -- Number of "Counts" per 1000 hours of operation in a given period

"Normalized Ranking" -- Data normalized against the highest value in the column, "Counts / (1k Operating Hours)"

"Pressure Fluctuation" Notes

"Avg. Hood Spray Pressure (psig)" -- Calculated from PI historian data

"Hours of Hood Spray Operation" -- "Hours of Hood Spray Operation" is a weighted value -- There is a 1.80 multiplier at 50 psig varying linearly to a 1.75 multiplier at 6 psig

"% of Total Operating Hours" -- The "weighted" hours of hood spray operation divided by the total number of operating hours -- converted to a percentage value

"Normalized Ranking" -- Data normalized against the highest percentage value in the column, "% of Total Operating Hours"

"Blade Fitment" Notes

"Blade Fitment" -- References the gap measurements for both the self-open assembly and the shroud 2-LOCK contact surfaces

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Executive Summary

Over the past 3 plus years, Duke Energy Florida LLC (Duke), at times working independently and at times together with Mitsubishi Hitachi Power Systems (MHPS), undertook a root cause analysis (RCA) of the cause(s) for the Unit 4S L-0 blade cracks and failures that occurred during normal station operations at Bartow Station. The intervals between failures had become shorter after each failure despite MHPS's attempts to improve the blades' performance and the station's adherence to the revised OEM operating instructions received after each successive failure.

Only after the telemetry test was completed and after the onset of Period 3, in approximately March 2015, (as a result of the telemetry test) did MHPS create an "avoidance zone" in which the station was not to operate except as needed to ramp up or down. Bartow operated in the avoidance zone only 1.15 hours in Period 4 and 0 hours in Period 5, but suffered two (2) further failures in successively shorter periods. Thus, after the fifth failure, Duke concluded that operation in MHPS' designated avoidance zone did not explain the failures and looked at whether other factors potentially were related or contributed to the failures.

Duke considered both operational and design aspects. With respect to operational factors, the Duke team used the Plant Information ("PI") data historian and operational data from each period and retroactively calculated¹ whether those factors had any correlation to the failures. Potential factors in the operational category included:

- Operations In MHPS Avoidance Zone -- Low Pressure (LP) Turbine "Excessive" Steam Flow
- Bartow Blending Operations – Potential Thermal Distress (Rate of Change in Super Heat Over Time, dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)

Duke Engineering concluded that there was no correlation between any one of the above-listed factors and the five (5) failure periods. Notably, Duke was only able to study each factor independently based on available data. In the absence of (1) blade telemetry, (2) duplication of the factors in various combinations, and (3) operation in varying but normal conditions, it is not possible to study how each factor relates to and interacts with any other factor, if at all.

Duke also studied design factors unique to MHPS 40" steel blades. This aspect of the RCA was largely deductive because MHPS controls design data, although MHPS did provide FEA stress and frequency analyses, material properties, and some dimensional information. The following factors were included in this portion of the study:

- Zone Analysis – Shroud Fretting Fatigue

¹ Because MHPS's operational constraint called the Avoidance Zone was not provided by MHPS until after the onset of Period 3, one could only look at hours in that zone after-the-fact for Periods 1 and 2.

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Name

- Background - pccimi comments
- Background
- Bartow RCA Final Review 11-9-16 Final R2
- Bartow RCA Report Out Questions 11-18-16 Slide 6 Rev1
- Bartow RCA Report Out Questions 11-18-16
- BRR RCA findings rev 1-17
- DRAFT Bartow RCA White Paper -- 10112017
- DRAFT Bartow RCA White Paper -- 10122017 BWM
- DRAFT Bartow RCA White Paper -- 10122017
- DRAFT Bartow RCA White Paper -- 10132017
- DRAFT Bartow RCA White Paper -- 10172017
- MHI aug 2012 period 1 rca
- RE_Requested Meeting Documents
- Requested Meeting Documents

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Name

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- [-] Bartow 4S Root Cause Analysis
- [-] Bartow L-0 RCA Draft Doc
- [-] Bartow L-0 RCA Executive Summary
- [-] Bartow RCA Chart (for RCA White Paper)
- [-] Bartow RCA Customer 9-22-17
- [-] Bartow RCA Customer 10-2-17
- [-] Bartow RCA Final Review 11-9-16 Final R2
- [-] Bartow RCA Report Out Questions 11-18-16 Slide 6 Rev1
- [-] Bartow RCA Report Out Questions 11-18-16
- [-] Bartow RCA White Paper -- 06262017
- [-] Bartow RCA White Paper -- 08232017 -- PVC and JCE Comments
- [-] Bartow RCA White Paper -- 09192017
- [-] Bartow RCA White Paper -- 10052017 - PVC comments (2)
- [-] Bartow RCA White Paper -- 10052017
- [-] Bartow RCA White Paper -- 10102017
- [-] Bartow RCA White Paper -- 08172017 -- PCrimi Comments
- [-] Bartow RCA White Paper -- 10052017 - PVC comments
- [-] Bartow RCA White Paper -- 10102017 PVC comments
- [-] Bartow Root Cause Analysis 2-6-18 (0000528275)
- [-] Bartow Root Cause Analysis 2-12-18 (0000528275)
- [-] DRAFT Bartow RCA White Paper -- 10112017
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- [-] DRAFT Bartow RCA White Paper -- 10132017
- [-] DRAFT Bartow RCA White Paper -- 10172017(2)
- [-] DRAFT Bartow RCA White Paper -- 10172017
- [-] RE_ Requested Meeting Documents
- [-] Requested Meeting Documents