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M A R I N A B A Y S A N D S



Repair of Severely Damaged Rotor as an Emergency Spare

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Presenters



Dr. Scot Laney

Senior Materials Engineer, R&D Team
Elliott Group, Jeannette, PA.

Joined Elliott in 2007 and has been involved with materials related R&D projects, failure analysis and aftermarket support. Also has experience in the areas of high temperature oxidation/corrosion and protective coatings.



Dr. Nicholas White

Machinery and Reliability Senior Advisor,
RasGas, Qatar

Responsibilities include asset rotating machinery surveillance, trouble shooting and reliability improvement. Previously held senior engineering positions in turbomachinery design for Cranfield University, Alstom Power and Kellogg Brown & Root



Douglas Richards

Senior Supervising Engineer,
Production Support Team
Elliott Group, Jeannette, PA

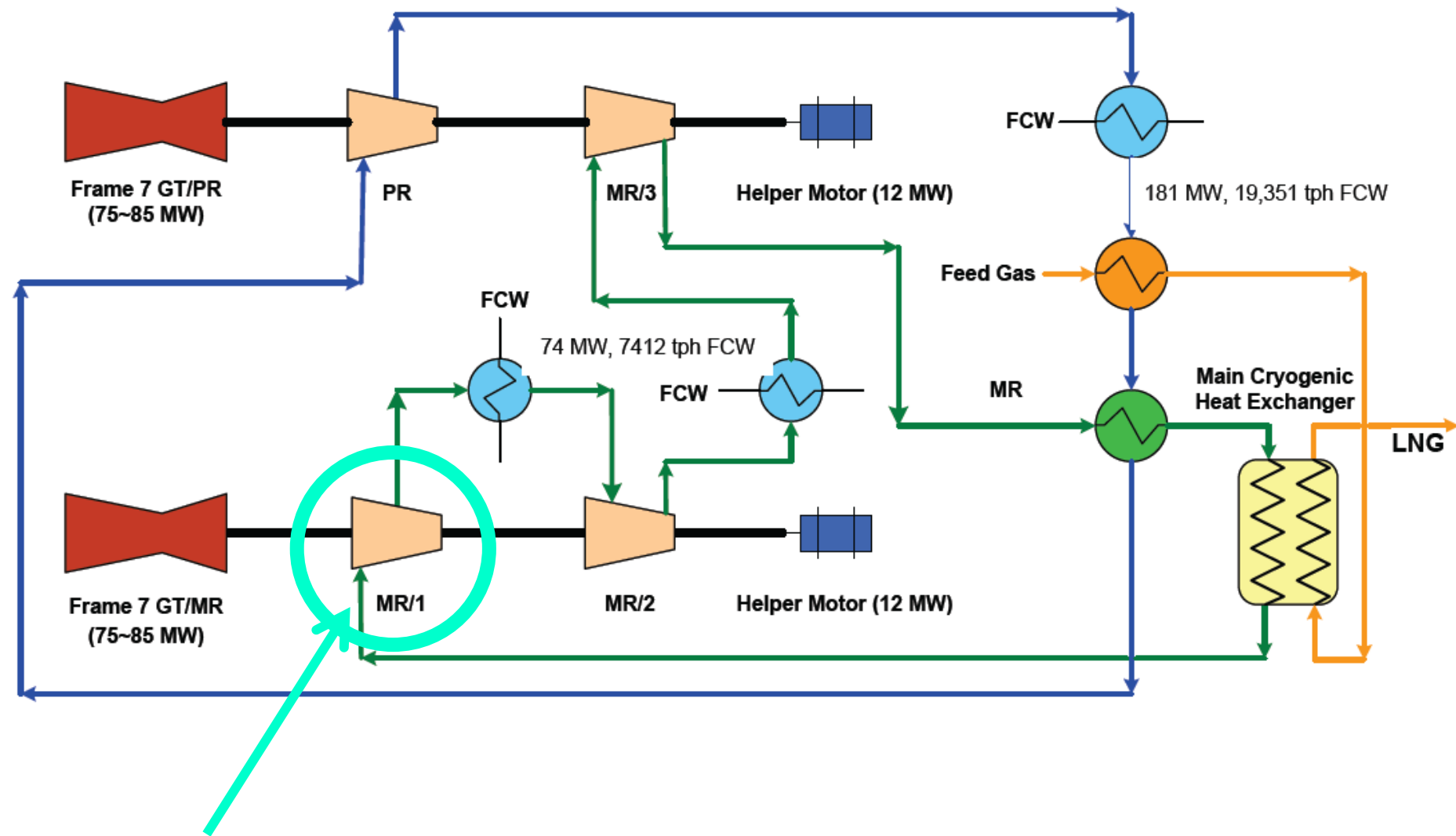
Joined Elliott in 1979 and has been involved with developing weld plans, creating and maintaining welding procedures and welder qualifications, and advising on production and service weld repairs.

Abstract

When the subject compressor was opened for an unrelated reason, it was unexpectedly found to have severe cracking, including a missing piece, on the first stage impeller and foreign object damage to the remaining three impellers. To mitigate risk while the common spare was running and a new rotor was manufactured, the subject rotor was repaired for use as an emergency spare. This case study discusses the extensive repairs performed to bring the rotor to a usable state.

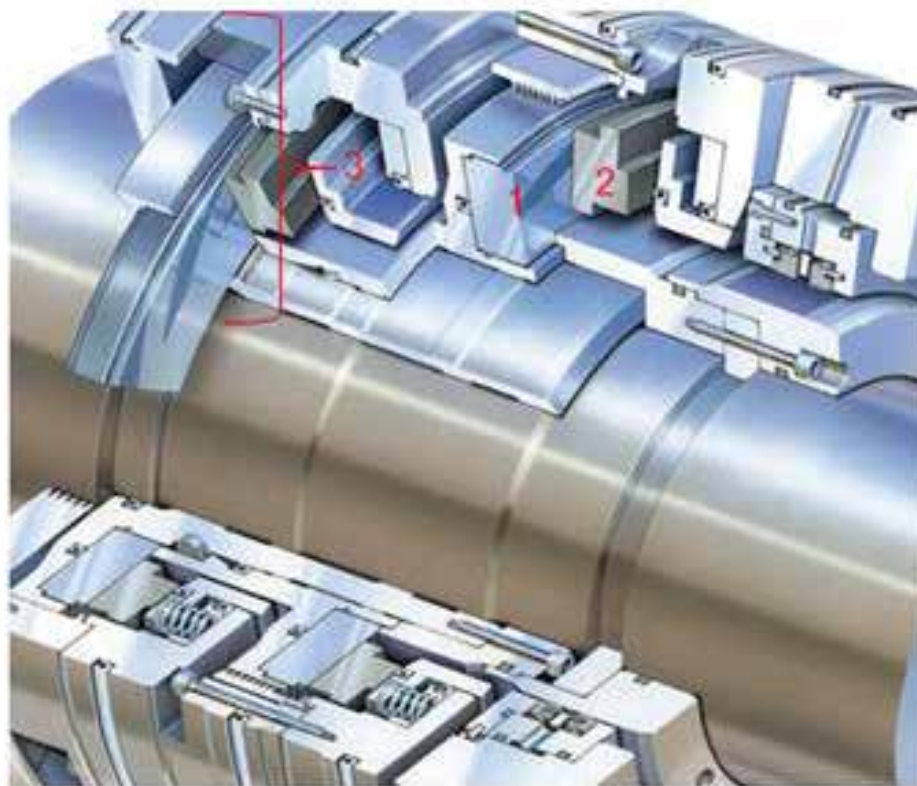
Background

- The End User operates seven LNG trains in their Ras Laffan, Qatar facility
- The trains are of the Air Products Inc. (APCI) propane, mixed refrigerant design
- Trains 3, 4, and 5 are identical with respect to compressor design and have a name plate rating of 5 MMTPA
- Train 5 is the newest and was commissioned in 2006 and has 8 years of service



Initial Problem

- In early 2014, the MR/1 compressor was shut down and opened due to a problem with the dry gas seal



Remains of NDE DGS



1 Secondary rotating ring

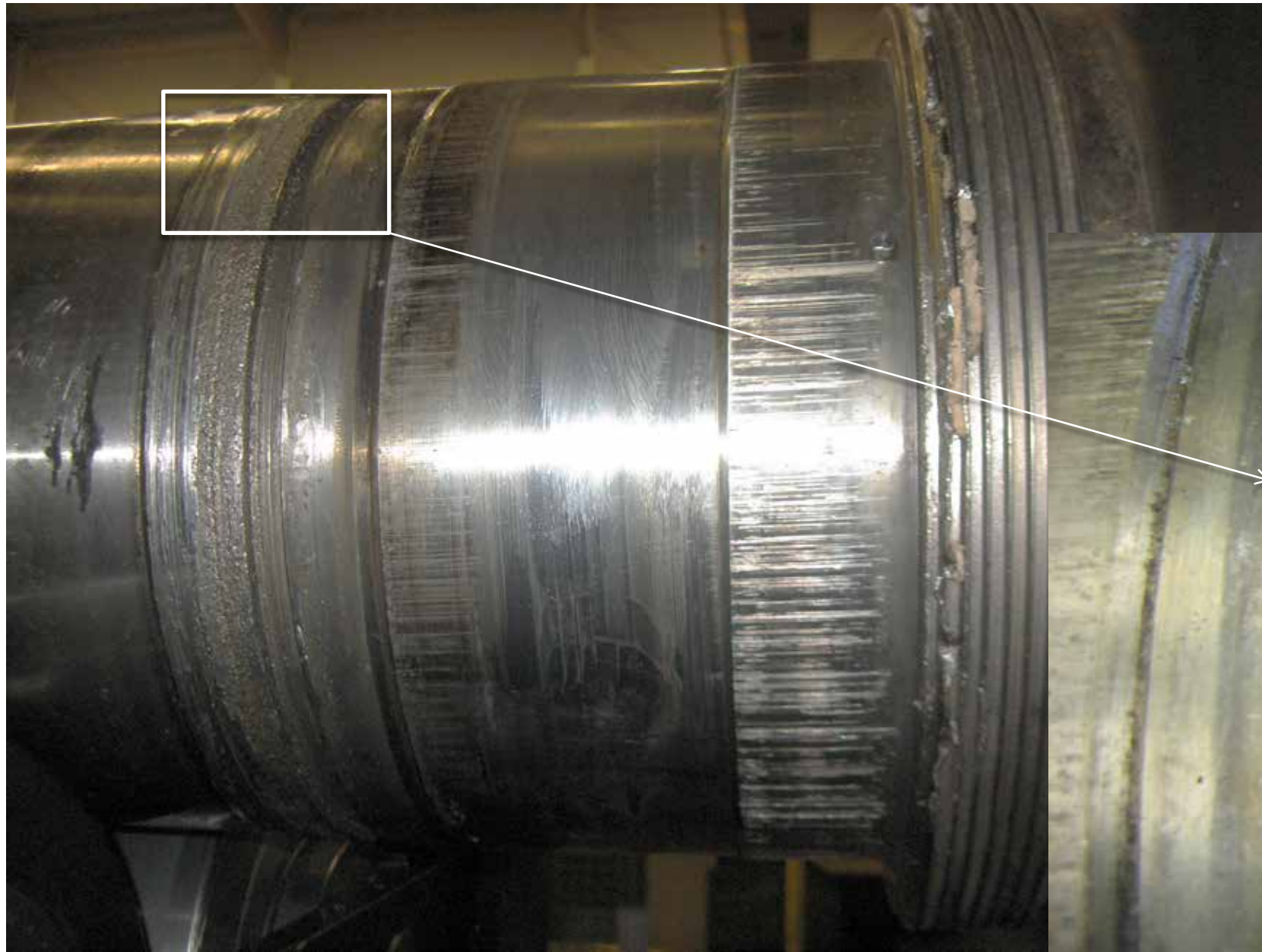


2 Secondary mating ring



3 Primary seal with plug vent & supply ports with melted part

Initial Problem



- Shaft had severe damage under the DGS



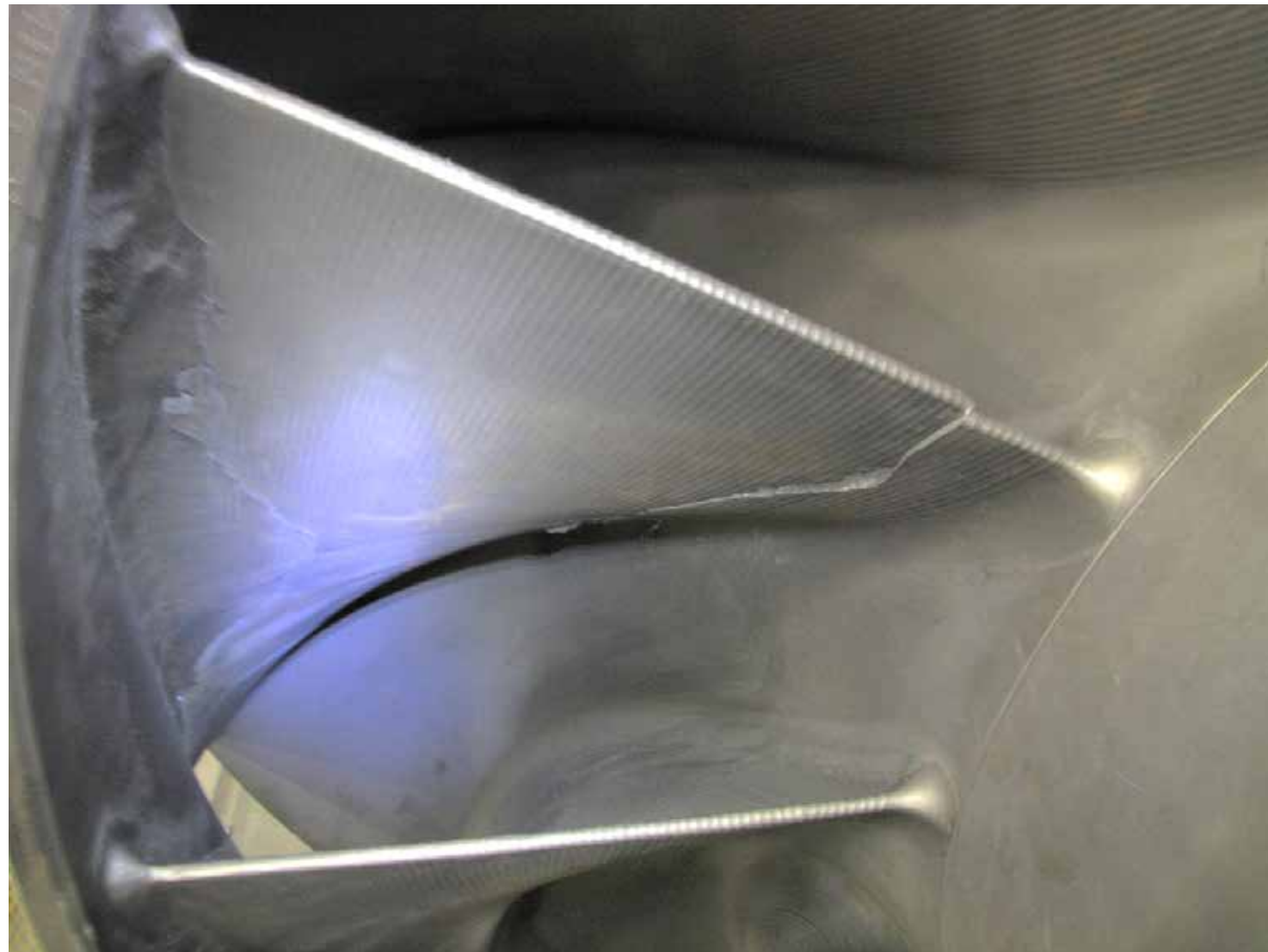
New Problem

- It was noticed that the first stage impeller had cracks in three blades
 - A large piece was missing from one of the cracks
 - There was a step change in the vibration early in the run, but no obvious indication that there was a problem
-
- As a result, the spare rotor was installed and the compressor restarted



New Problem

- Cracks in this blade extend from the eye nearly to the tip



New Problem



- A liberated piece struck the adjacent blade, initiating a crack
- There was much more of the piece missing than found



New Problem Expands

2nd Stage



- Virtually every blade in stages 2-4 have FOD at the leading edge

New Problem Expands

3rd Stage



4th Stage



Damage Summary

Shaft has severe wear and scoring damage

First impeller is severely cracked and missing a piece

Remaining impellers have major FOD

Thrust disk has fretting on the fits

+ Shaft sleeves are dinged

Entire rotor is considered scrap

Determining Next Steps

- The rotor is sent to the OEM's service facility closest to its headquarters for ease of access to engineering for the RCFA
- For operational purposes, the End User wished to minimize the time to replace the failed rotor
- A new rotor will take 6 months to build
- During the RCFA kick off meeting, End User requests a RCFA be performed and evaluations be made to determine if the rotor is salvageable as an emergency spare
- The OEM's engineers make a high level review of the situation and determine repair could be possible
- Plans are made for a minimally invasive metallurgical portion of the RCFA while more in depth review is made

Evaluation of 1st Stage Impeller

- Welding Engineers evaluated for ability to weld repair
 - Due to the size of the impeller, accessibility is not an issue
 - Impeller material is 13Cr-4Ni heat treated to give optimal strength and toughness at -101°C
 - Given that the 13Cr-4Ni material is extremely weldable and is the OEM's standard for most impellers, weld procedures and qualifications are already in place
 - With proper fixturing, crack removal, and inspection the impeller could be repaired to a like new condition

Evaluation of 2nd, 3rd, & 4th Stage Impellers

- The impellers are NDT'd
- Depth of every ding/crack on the 2nd, 3rd, and 4th impellers is measured and recorded to determine best course for repair
- Most dings are 6.35mm (0.25") or less

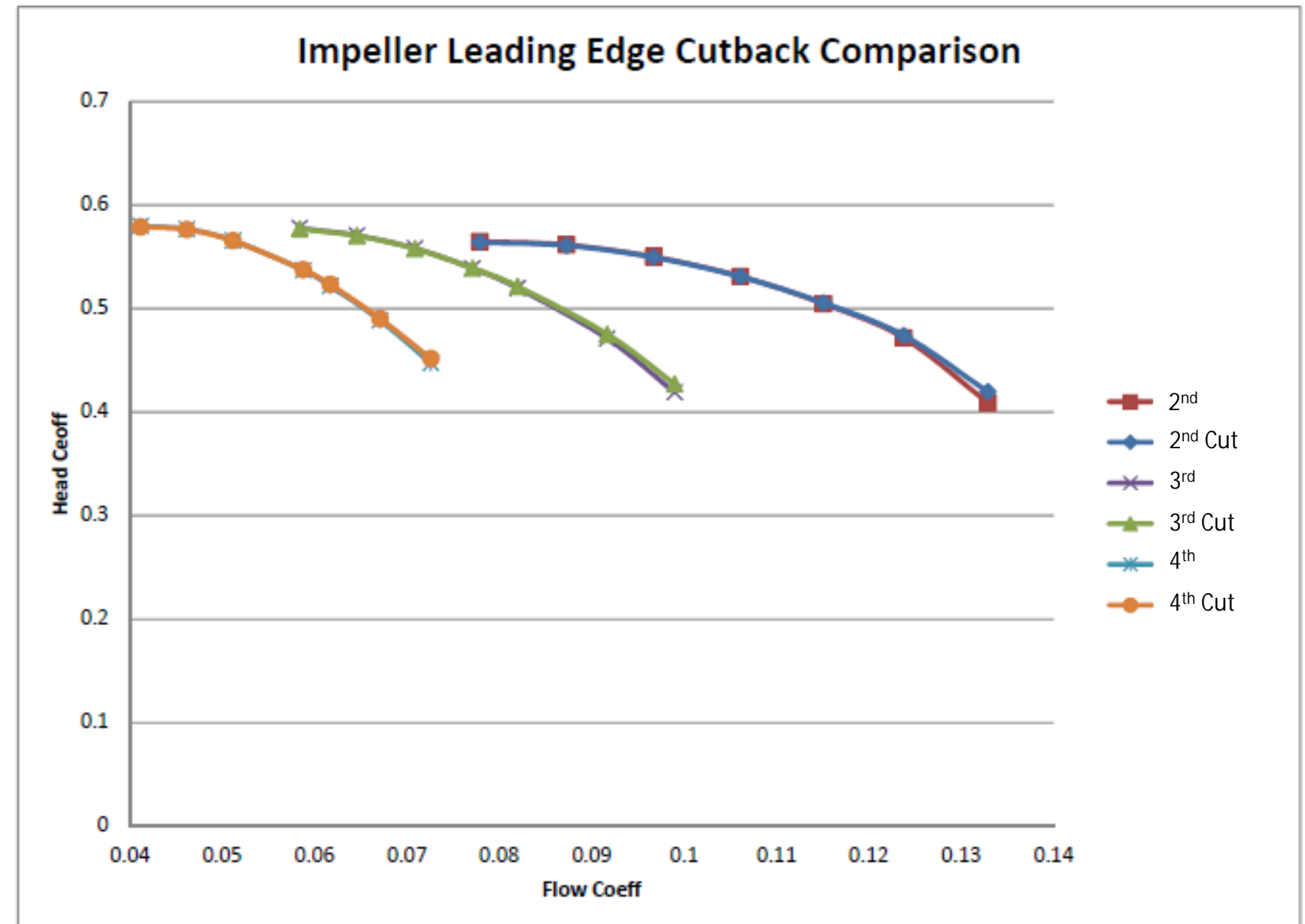
Blade Number	Stage 2 depth (mm)	Stage 3 depth (mm)	Stage 4 depth(mm)
1	6.35, 4.75, 6.35	6.35, 6.35	6.35, 4.75, 6.35
2	6.35, 4.75	6.35	4.75, 6.35
3	6.35	7.95, 7.95	6.35, 4.75
4	7.95, 4.75	6.35	6.35
5	4.75, 4.75	6.35, 6.35	4.75, 4.75
6	4.75, 7.95, 6.35	6.35	3.20, 6.35, 6.35
7	6.35, 6.35, 7.95	6.35, 6.35	4.75, 6.35
8	4.75, 4.75	6.35, 6.35	6.35, 6.35, 6.35
9	6.35	6.35, 6.35	4.75, 3.20
10	7.95, 6.35	6.35	6.35, 6.35
11	7.95, 9.5	6.35, 6.35	4.75, 3.20
12	6.35, 6.35	6.35	6.35, 3.20
13	4.75	7.95, 6.35	6.35, 6.35
14		6.35	6..35
15		6.35, 6.35, 6.35	6.35, 6.35

Evaluation of 2nd, 3rd, & 4th Stage Impellers

- Decided that the fastest, easiest, and most effective method to remove the damage is to machine back the leading edge of every blade by 6.35mm (0.25") and hand radiusing the new leading edge
- Structural and Aero impacts are minimal

Speed Held Constant	
	%diff
Pressure	0.31%
Head	0.22%
Power	0.34%

Discharge Pressure Held Constant	
	%diff
Speed	-0.06%



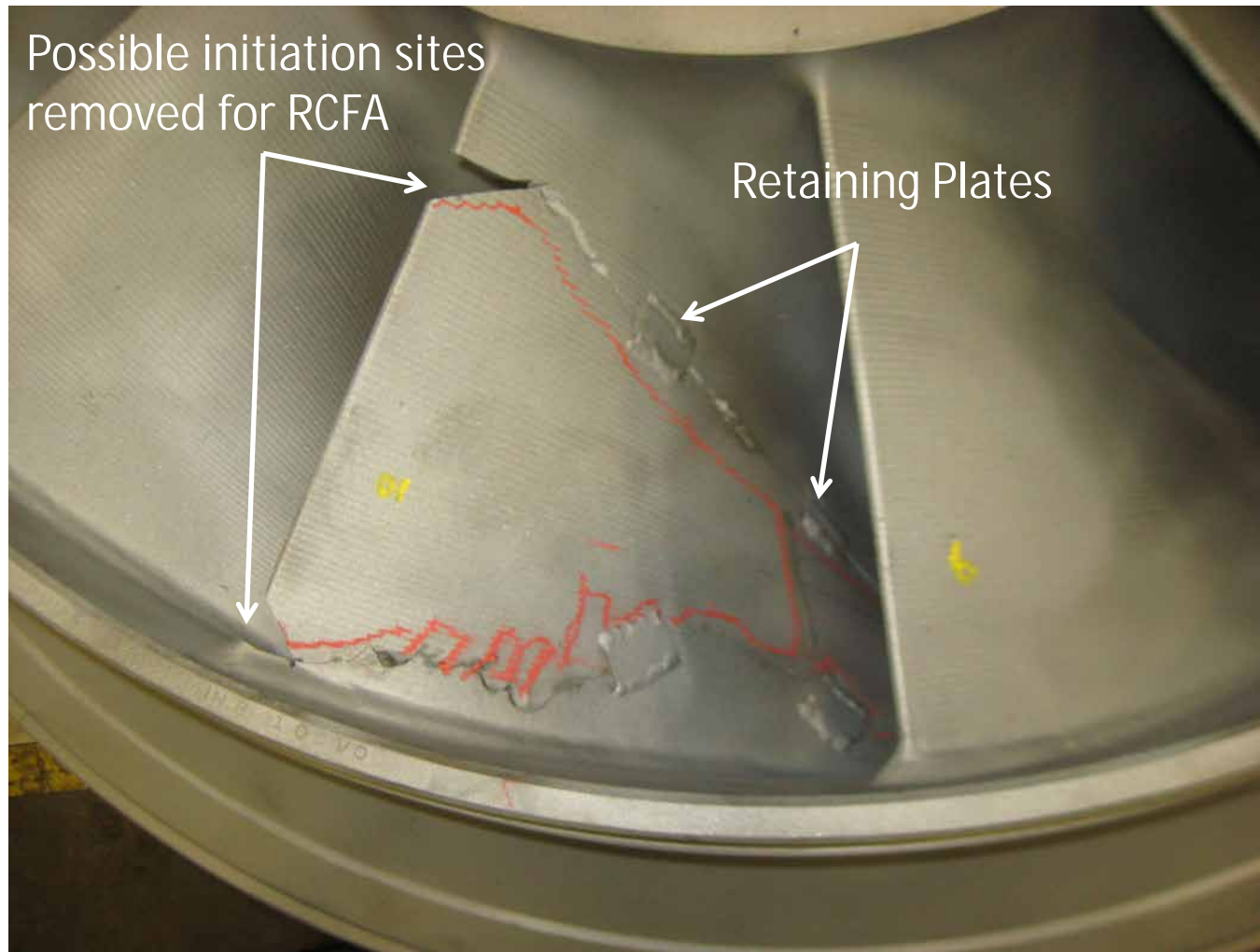
Evaluation of Shaft

- Weld repair of the shaft is typical repair for the type of damage, but would likely negatively affect the schedule
- Estimates of the depth of grinding required to clean up the shaft to an adequate state was acceptable with respect to design allowances
- Dry gas seal vendor was contacted to determine if custom hardware could be designed to accommodate the new shaft dimensions with existing stationary dimensions

Decision

- Performance loss associated with cutting back the leading edges of Stages 2-4 is acceptable to the End User in an emergency situation
- It is agreed that overspeed test of the 1st impeller after repair and at speed balance of the rotor serve as verification of the structural integrity
- Both parties agree to proceed with the repair

Repair of 1st Stage



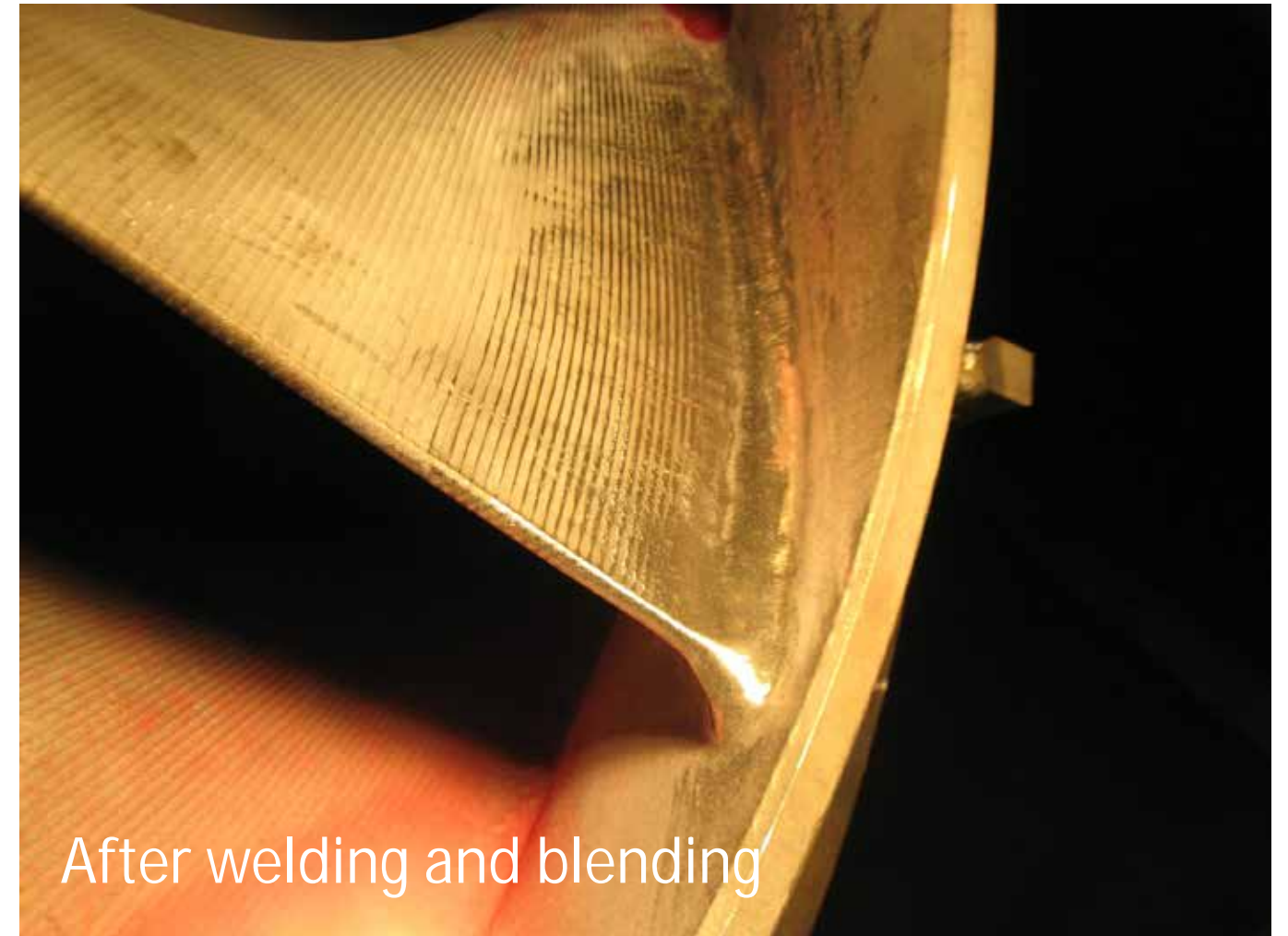
- Impeller fixtured and mounted on a positioner
- Plates welded on at various locations to hold the loose pieces in place
- For the RCFA, samples of possible crack initiation sites taken from where the crack breaks the leading edge
- Visible crack removed by grinding, NDT'd and any remaining indications removed

Repair of 1st Stage



- Crack free grooves were welded (full penetration)
- Support plates removed and areas underneath welded
- Weld blended

Repair of 1st Stage



- Piece of adjacent blade removed for RCFA
- Crack ground out, NDT, remove any remaining cracks
- Weld and blend

Repair of 1st Stage



- Rough depth and height dimensions measured
- Area of interest taken from 3D model and replacement piece 5 axis milled from block of 13Cr-4Ni

Repair of 1st Stage



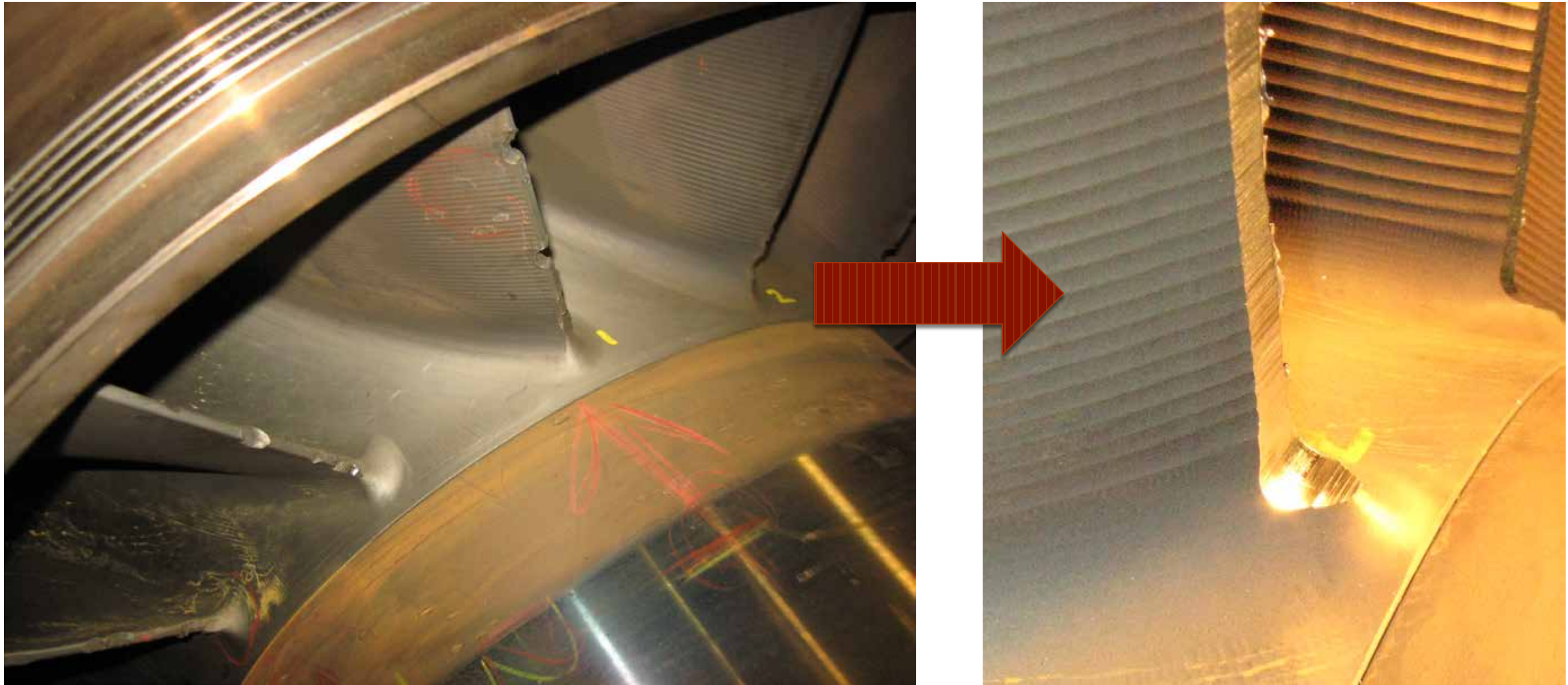
- Crack ground out, NDT'd, then the surface smoothed and prepped
- Replacement piece machined to fit in place, prepped, and tacked
- Copper backing plate clamped to the back side and front side welded
- Copper plate removed, weld back gouged and weld back side

Repair to 1st Stage



- Welds blended in
- Completed impeller was stress relieved per weld procedure
- Over speed tested at max continuous for 2 min. to ensure structural integrity

Repair of Stages 2, 3, & 4



Leading edge of all blades were machined back ~6.35 mm (1/4") while still on the shaft

Repair of Stages 2, 3, & 4



Leading edge of all blades were blended by hand with a radius tool



Shaft End After Machining



Shaft end was machined until it was mostly cleaned up.

Rotor Assembly

- Rotor was restacked
- All welds were blended 1" into the eye and tip
- Shot peened all welds in the blended area



- All the typical dimensional, residual magnetism, and runout checks were completed with no issues
- Rotor was at speed balanced with no issues



Conclusion

- Emergency rotor was shipped back to End User ~2 months after the initial RCFA meeting
- New rotor was shipped on schedule 4 months later and included some upgrade modifications
- The spare rotor that was installed in the machine is still running
- With proper circumstances and engineering analysis, while not suggested, repairs of this nature are possible