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GAS TURBINE MATERIALS LIFE ASSESSMENT AND NONDESTRUCTIVE EVALUATION

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Project Overview

- Team member: Siemens Corp. and Argonne National Lab
- Research focus: gas turbine materials
  - For higher-temperature engine operations to improve efficiency and reduce emissions
  - For the use of unconventional fuels with more corrosion species
- Project tasks:
  - Task 1: develop predictive models for deposition, corrosion and component life assessment
  - Task 2: develop/demonstrate nondestructive evaluation (NDE) technologies for coatings
- Project duration FY2015-FY2017

Task 1: Corrosion Test - Purpose

- To evaluate the corrosion effects on turbine materials for syngas and steam/CO_2 environments.
- The investigation involves testing of materials in support of H_2 Turbine and Zero Emission Power Plant (ZEPP) program being conducted at Siemens.
- This project builds on existing gas turbine technology and product developments, and will develop, validate, and prototype test the necessary turbine related technologies and sub-systems needed to demonstrate the ability to meet the DOE turbine program goals.

Task 1: Approach

- Perform high temperature corrosion tests on turbine alloys and coatings
  - work performed by Zuotao Zeng and Ken Natesen at ANL

Materials

1. Alloy samples such as IN939, CM247, Rene80, X45, ECY768, and IN738.
2. Alloys coated with NiCoCrAlY overlay layers.

Material	C	Cr	Ni	Mn	Si	Mo	Fe	Other
Rene80	0.17	14	60	-	-	4.0	-	Al 3.0, Co 9.5, Ti 5.0, W 4.0, B 0.015, Zr 0.03
CM247	0.15	8	Bal	-	-	0.5	-	Al 5.5, Co 9, W 10, Ta 3.2, Ti 0.7, Hf 1.4, B 0.015, Zr 0.01
IN-939	0.15	22.5	48	-	-	-	-	Al 1.9, Co 19.9, W 2.0, Ta 1.4, B 0.009, Zr, 0.09
IN738	0.17	16				1.7	-	Co 8.5, Nb 0.8, Ti 3.5, Al 3.5, Zr 0.1, B 0.01
X45	0.2-0.3	24.5-26.5	9.5-11.5	.75-1	0.4-1	-	2	Co 54.6, W 7-8, B 0.005-0.015, P<0.04, S<0.04
ECY 768	0.6	23.5	10	-	-	-	1	Co 54, W 7, Ta 3.5, Ti 0.2, Al 0.15, Zr0.05, B 0.01

Test Samples – Provided by Siemens

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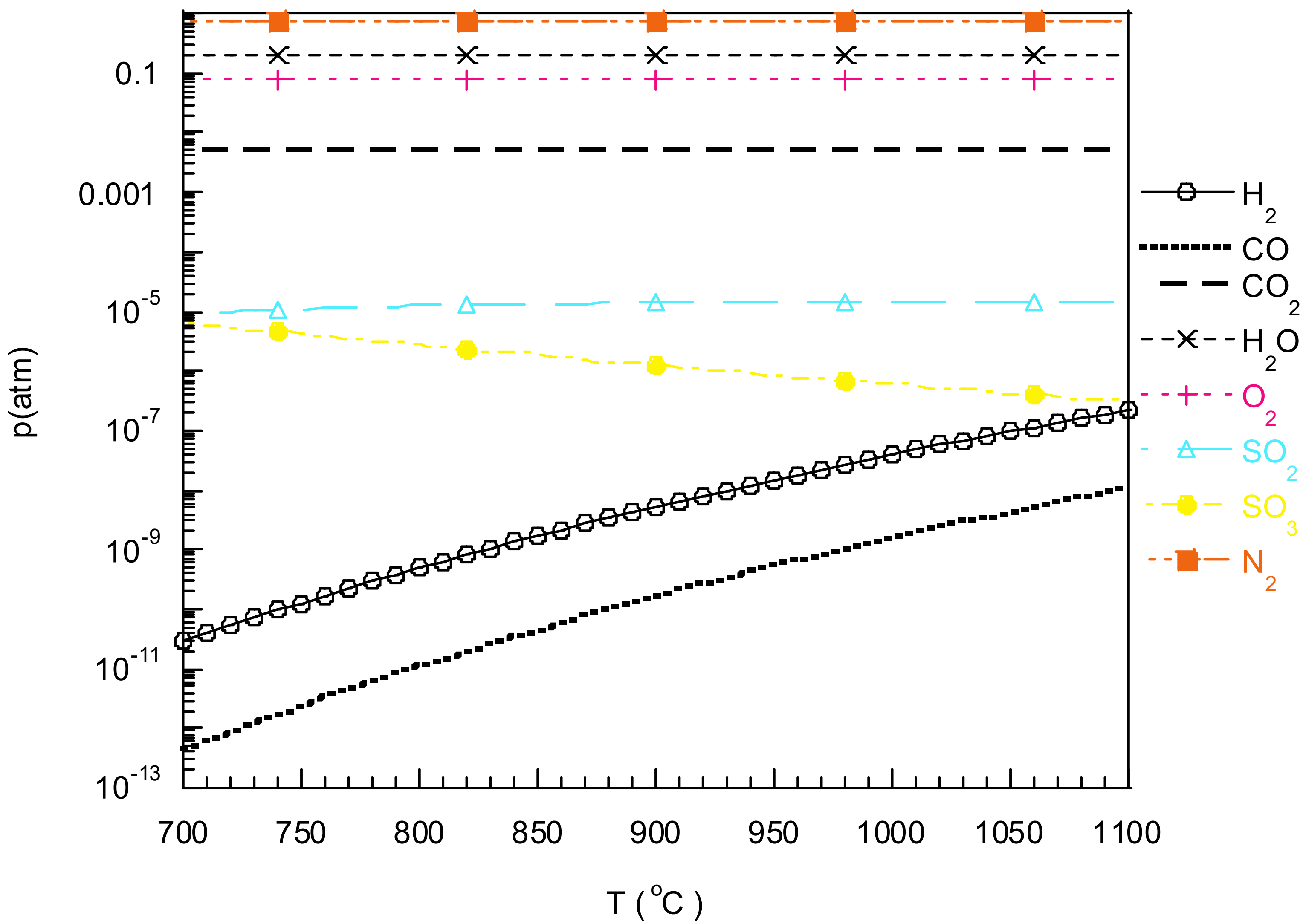
Experiment Conditions and Analysis Methods

- Gases: Air combustion gas #1, Air combustion gas #2, and Oxy-fuel gas #3.
- Temperatures: 950 °C and 1010 °C.
- Time: 500, 1000, and 2000h.

Composition	Gas #1	Gas #2	Gas #3
H_2O (vol %)	20.5	17.1	89.8
CO_2 (vol %)	0.5	4.8	10
O_2 (vol %)	7.65	12.6	0.2
Ar (vol %)	0.7	-	
N_2	Balance	Balance	
CO ppm	10	10	
SO_2 ppm	15	15	

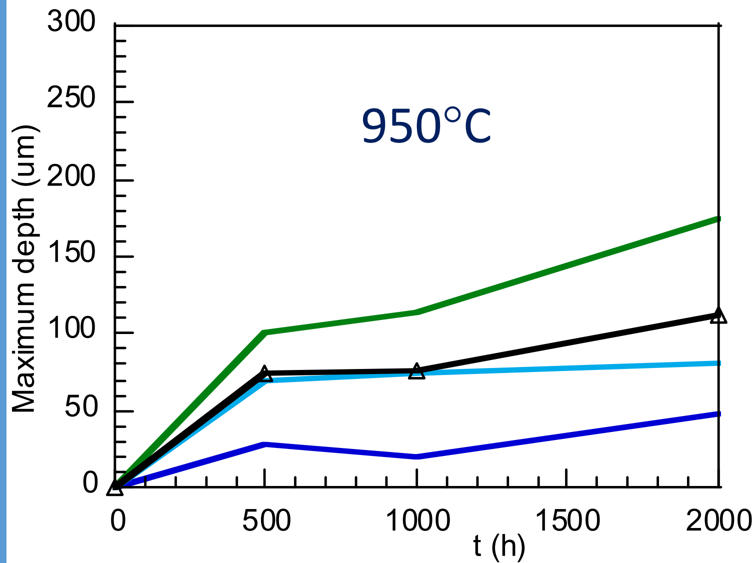
- Samples were weighed before and after test.
- Samples were cut and mounted to cross section for SEM analysis after test. Corrosion depths were measured from SEM cross section analysis.
- EDX analysis was performed for some samples.

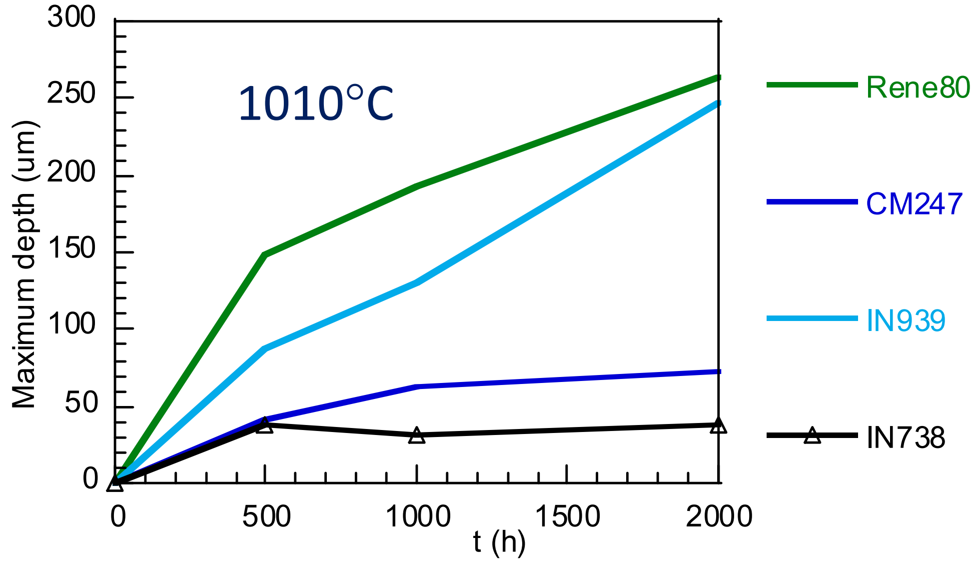
Partial Pressure for Gas 1



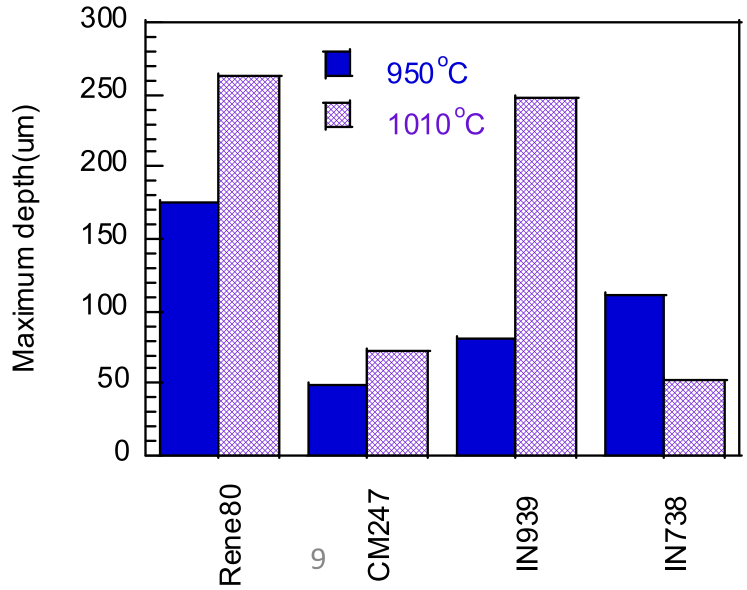
Effect of Temperature on Alloys

Gas #1: 20.5%$H_2$0, 0.5%CO_2, 7.65%O_2, 10ppmCO, 15ppm SO_2, N_2 balance





Generally corrosion rates are higher at higher temperature, but IN738 is abnormal.



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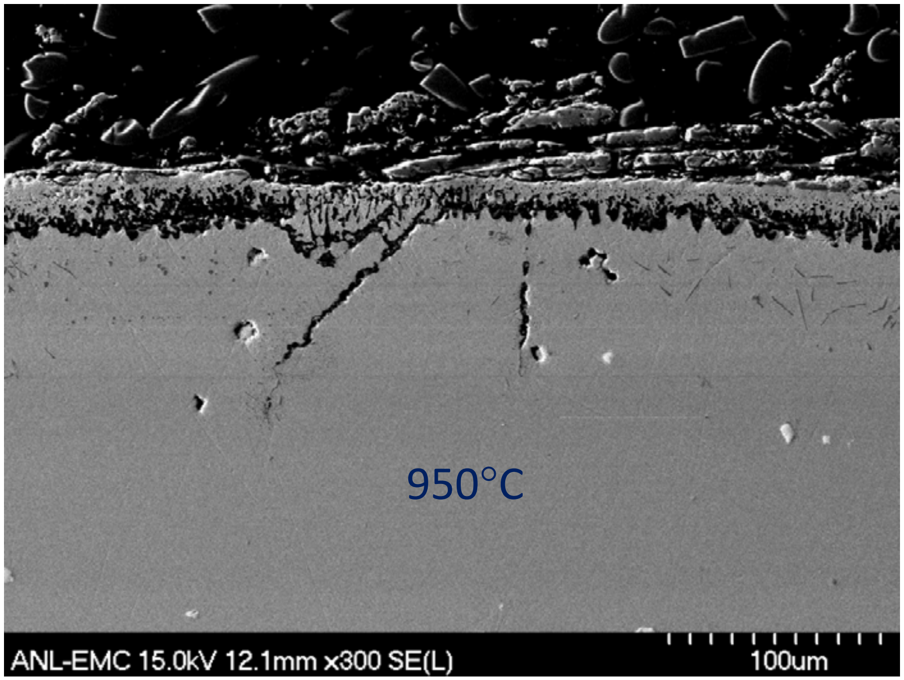
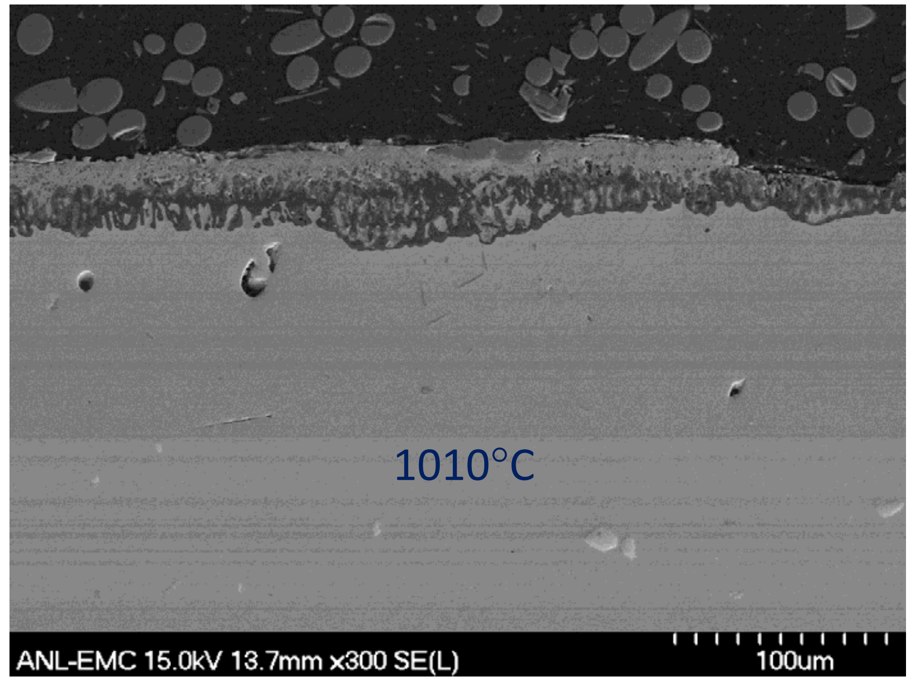
Micrographs of Alloy IN738

Gas #1: 20.5%H_20, 0.5%CO_2, 7.65%O_2, 10ppmCO, 15ppm SO_2, N_2 balance

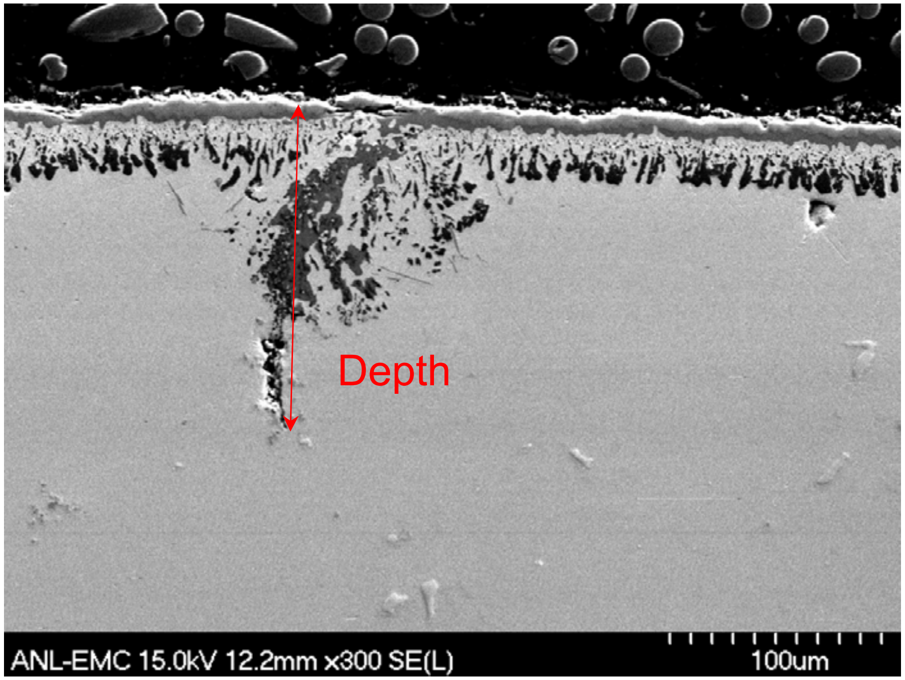




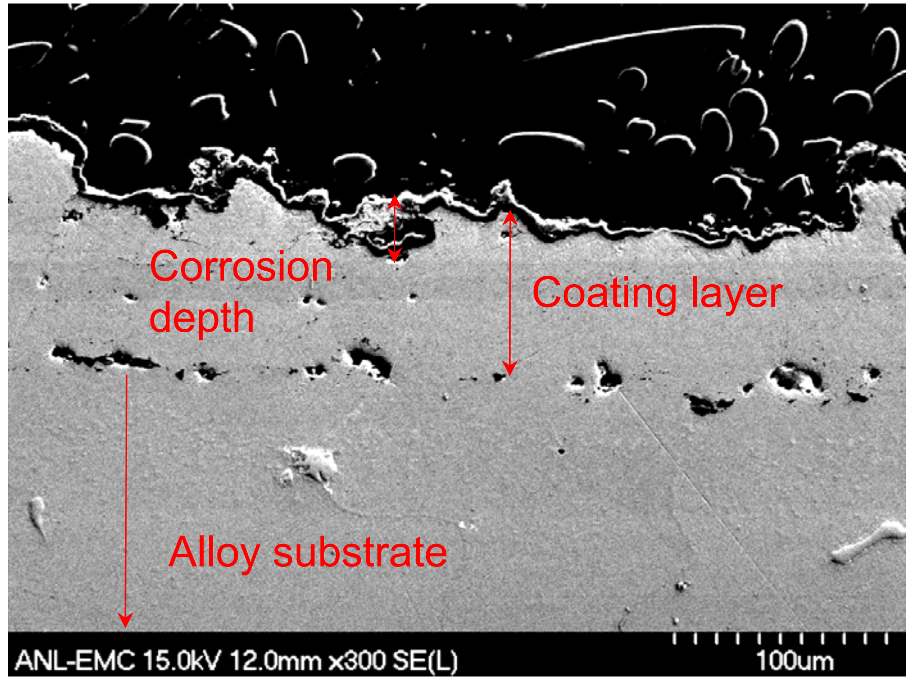
In738, Gas #1, 2000h, deep internal oxidation is observed at 950°C.

Protect Alloy Substrate by Coating

Gas #1: 20.5%$H_2$0, 0.5%CO_2, 7.65%O_2, 10ppmCO, 15ppm SO_2, N_2 balance



RE80

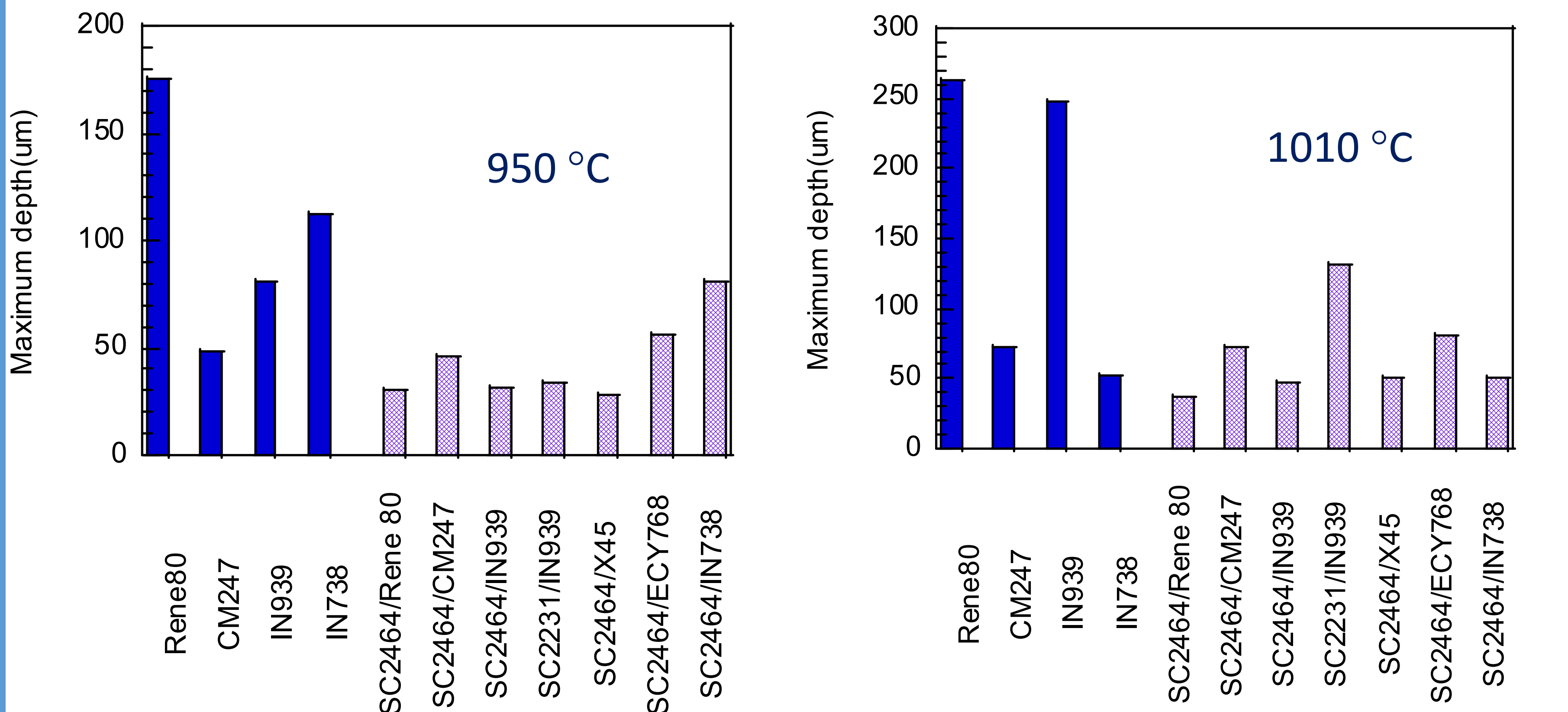


SC2464/RE80

950°C, 2000h

Maximum Depths in Alloys and Coatings

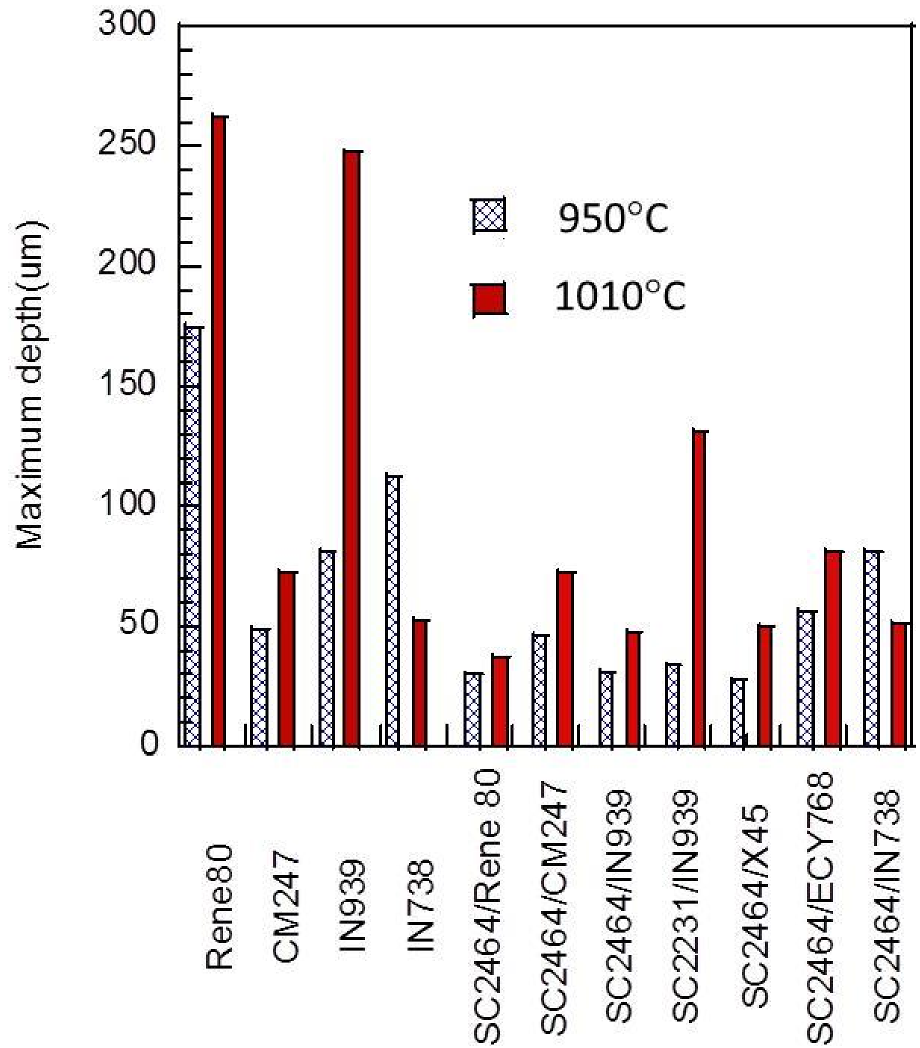
Gas #1: 20.5%H_20, 0.5%CO_2, 7.65%O_2, 10ppmCO, 15ppm SO_2, N_2 balance



Effect of Temperature on Alloys and Coatings

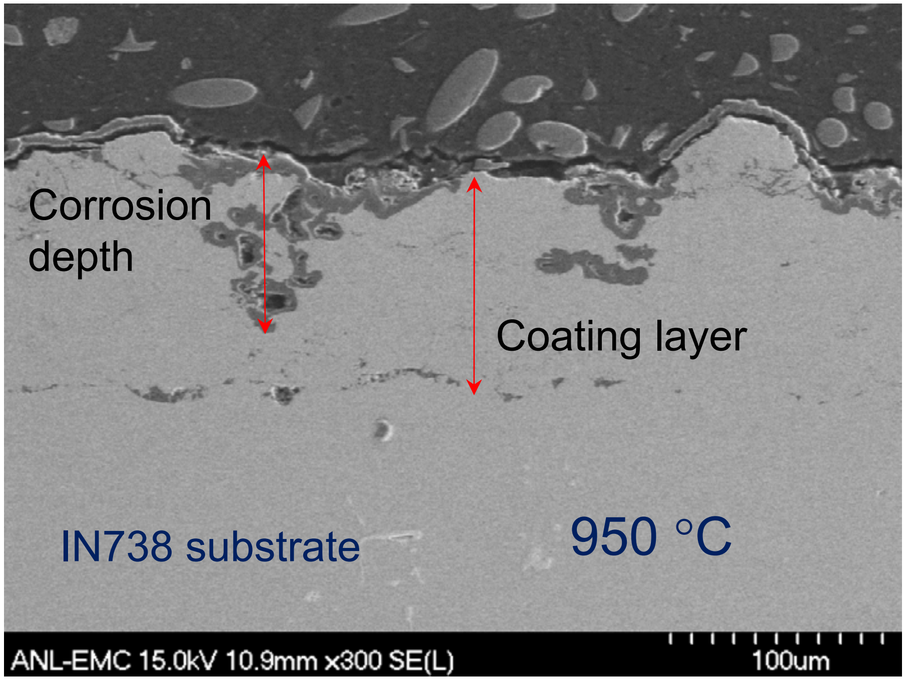
Gas #1: 20.5%$H_2$0, 0.5%CO_2, 7.65%O_2, 10ppmCO, 15ppm SO_2, N_2 balance

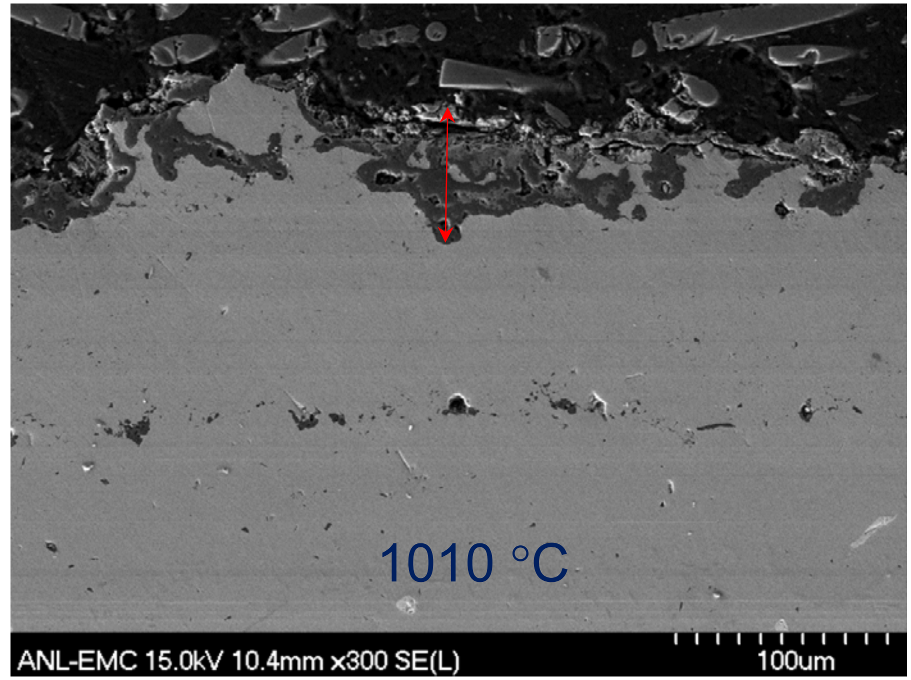
Temperature 950 and 1010°C



Generally corrosion rates are higher at higher temperature

Corrosion in Coating SC2464/IN738





For coating SC2464/IN738, corrosion depth after exposure to Gas #1 at 950°C for 2000h is higher than at 1010°C.

Reason? Not sure whether is due to the quality of coating? Need more test to confirm.

Task 1: Summary

- Completed analysis on the test specimens in air combustion gas environment (Gas #1) at 950 °C for 500h, 1000h, and 2000h.
- Corrosion rates of coatings are generally higher at higher temperature after exposure to air combustion Gas #1.
- All coatings prevented breakaway oxidation at 950°C up to 2000h.

Task 1: Plan for FY2017

	Test #1a	Test #1b	Test #1c	Test #2a	Test #2b	Test #2c	Test #3a	Test #3b	Test #3c
Temperature (°C)	950	950	950	950	950	950	950	950	950
Gases	Gas #1	Gas #1	Gas #1	Gas #2	Gas #2	Gas #2	Gas #3	Gas #3	Gas #3
Time (h)	500	1000	2000	500	1000	2000	500	1000	2000
	Running	Running	planned	planned	Planned	Planned	done	done	done
	Test #4a	Test #4b	Test #4c	Test #5a	Test #5b	Test #5c	Test #6a	Test #6b	Test #6c
Temperature (°C)	1010	1010	1010	1010	1010	1010	1010	1010	1010
Gases	Gas #1	Gas #1	Gas #1	Gas #2	Gas #2	Gas #2	Gas #3	Gas #3	Gas #3
Time (h)	500	1000	2000	500	1000	2000	500	1000	2000
	done	done	done	done	done	planned	done	done	done

- There are 18 tests for this project. We have finished 14 tests (see the yellow parts in the test chart). The testing will be continued and the tested specimens will be characterized via weight change vs. time, microscopy, coating appearance (disbonding, cracking, etc.) and comparison of coating data with those of uncoated alloys.

- Development of a model capable of thermo-kinetic modelling of contaminant flux and extrapolation for high temperatures/high pressures for the establishment of corrosion maps for high temperature metallic and ceramic systems will be carried out.

Task 1: Acknowledgements

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References

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2. Z. Zeng, K. Natesan, Z. Cai, D.L. Rink, Effects of calcium in ash on the corrosion performance of Ni-based alloys in simulated oxy-fuel environment, FUEL, 178, 10-22 (2016).
3. Z. Zeng, K. Natesan, Z. Cai, D. Gosztola, R. Cook, and J. Hiller, Effect of element diffusion through metallic networks during oxidation of Type 321 stainless steel, Journal of Materials Engineering and Performance, 23, 1247-1262 (2014).
4. Z. Zeng, K. Natesan, Z. Cai, D.L. Rink, Effect of coal ash on the performance of alloys in simulated oxy-fuel environments, FUEL, 117, 133-145 (2014).

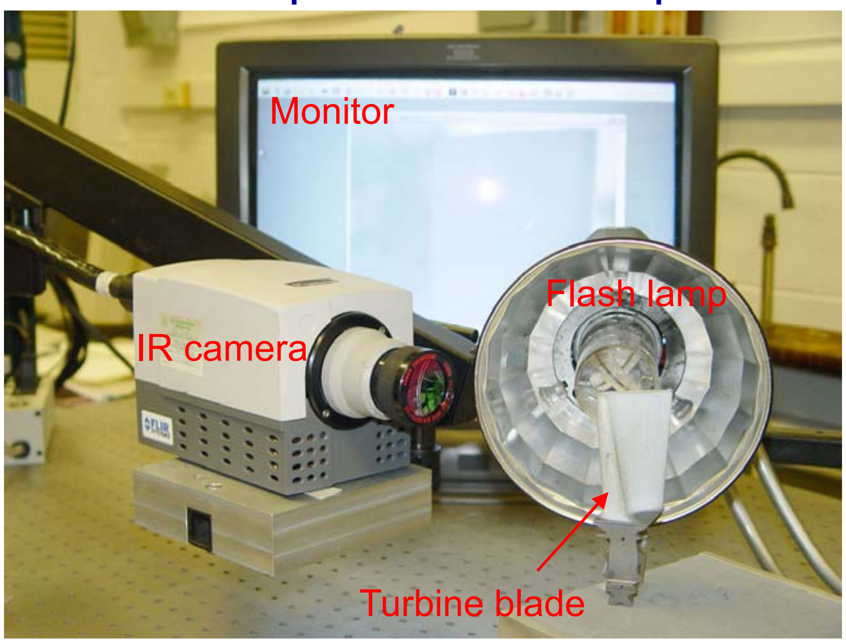
Task 2: NDE Development - Objective

- Develop and demonstrate advanced thermal-imaging NDE technologies for coatings
  - For coating quality inspection
    - Coating property measurement: multilayer analysis (MLA) method
    - Coating defect detection: thermal tomography (TT) method
  - For TBC life prediction
    - Modeling of TBC property degradation with life

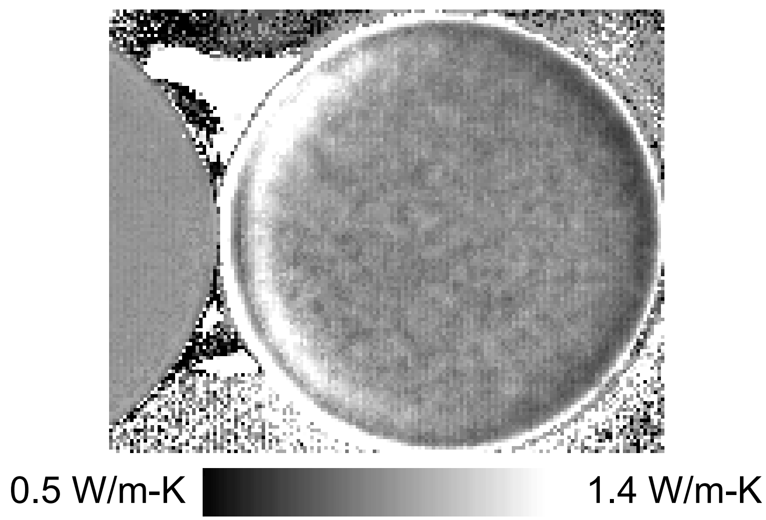
Pulsed Thermal Imaging – Multilayer Analysis (PTI-MLA)

- PTI-MLA consists of a pulsed thermal imaging (PTI) experimental system and a multilayer analysis (MLA) data-processing code
- PTI-MLA images two coating properties over entire coating surface
  - thermal conductivity and heat capacity (or thickness)

PTI experimental setup



Thermal conductivity imaging



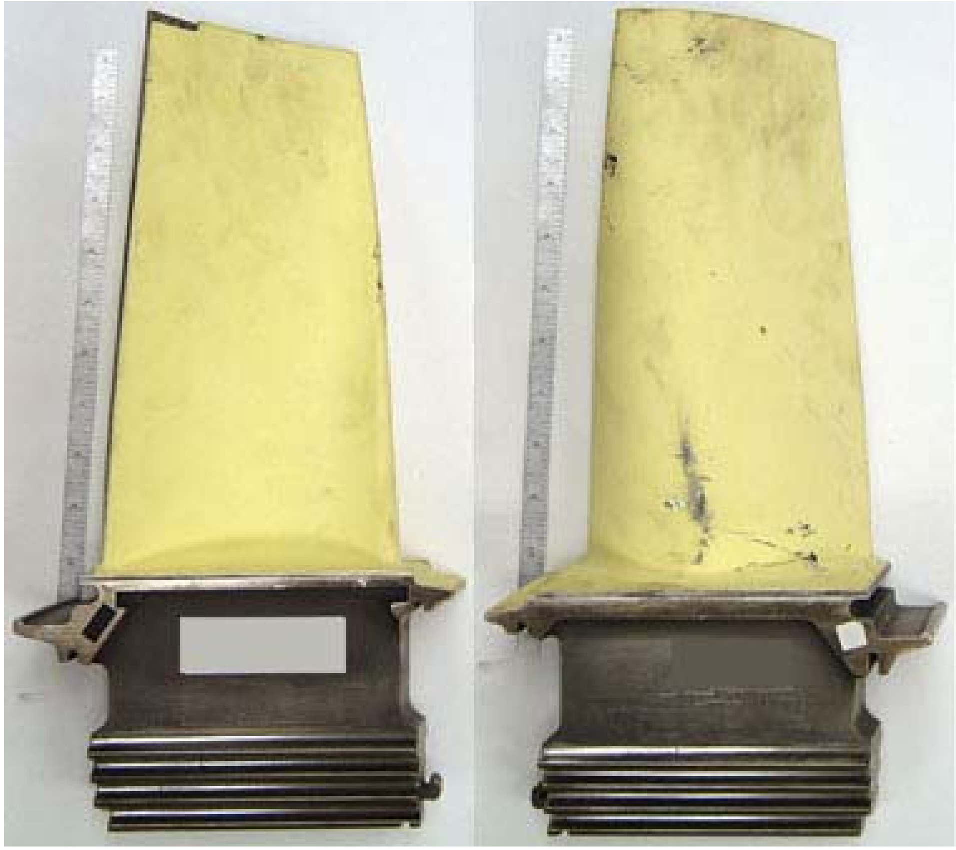
Task 2: Recent NDE Development

- Thermal imaging multilayer analysis (MLA) method was validated suitable for NDE of entire TBC lifetime

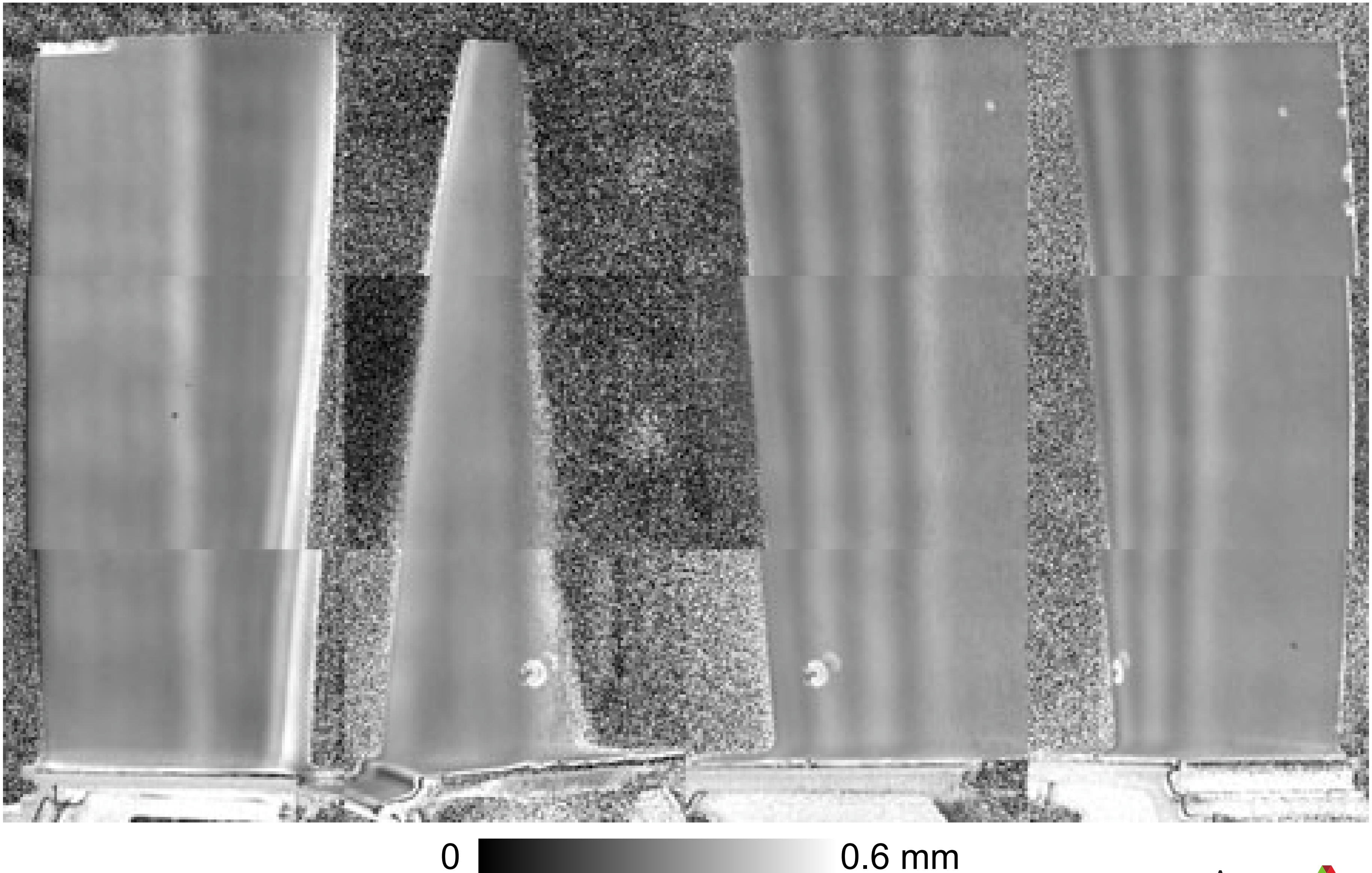
- Developments of MLA for engine component inspection
  - Mapping MLA data on 3D engine components
  - Evaluation of low-cost IR camera

NDE for TBCs on Engine Components

- PIT-MLA can easily obtain NDE data for entire engine part
- However, entire NDE data may be difficult to present if part is complex
- Example for a simpler part: engine blade



TBC Thickness Image for Entire Blade (total 12 sub-images)



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Why 3D Mapping of NDE Image Data?

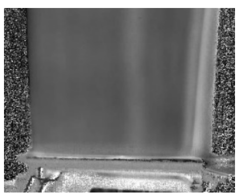
- Current NDE image data are simply compiled in presentation
- Such NDE results can be difficult to use:
  - Difficult to understand NDE images if part is very complex
  - Difficult to read TBC property if the surface is overlapped (data with different signal-to-noise ratio)
  - Difficult to perform dimensional analysis because length scale varies
  - Difficult for TBC life prediction because each inspection may be taken from different viewing directions so not directly comparable
- Solution: mapping and stitching all NDE sub-images onto surface cloud points of 3D part → NDE data are on a fixed coordinate system

3D Mapping for NDE Image Data

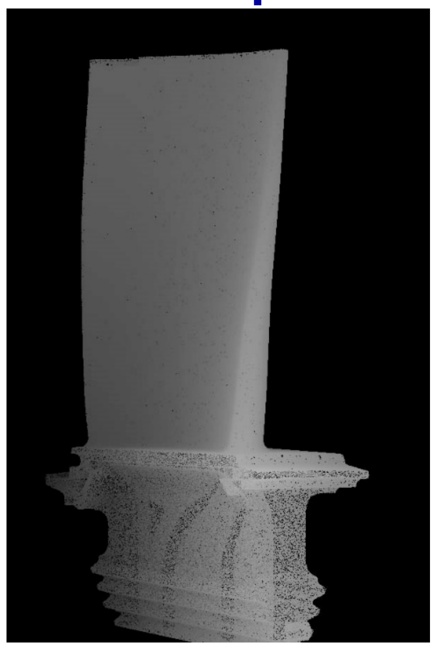
- Input data:
  - Surface cloud points of 3D part
  - NDE images (for entire 3D part surface)
- Step 1: Calculating normal vectors of cloud points (if not available)
- Step 2: Mapping/stitching NDE images onto surface cloud points
  - Matching each NDE test image with corresponding projection image of 3D part and transferring NDE data to surface points
  - Automated weighting to eliminate data with poor or no flash heating
  - Result: all NDE sub-images are seamlessly stitched onto surface cloud points of 3D part
- Step 3: 3D NDE data can be displayed in any views (or videos)

Matching NDE Image with Projection Image of 3D Part

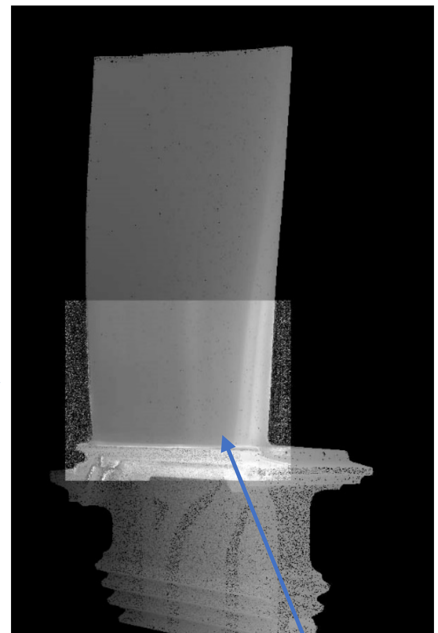
NDE image



Projection image of cloud points

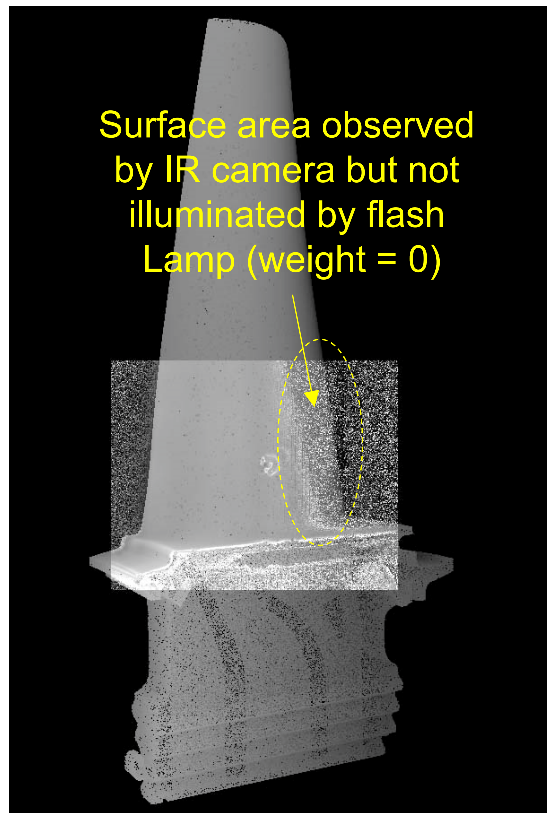


Matched image

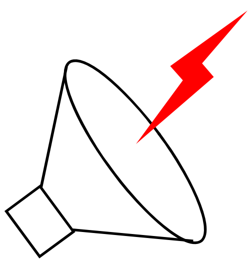


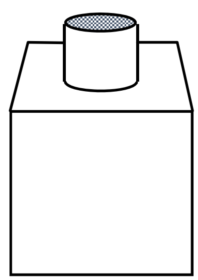
NDE data on image pixels are transferred to surface points

Weighted Data in Overlapped Areas

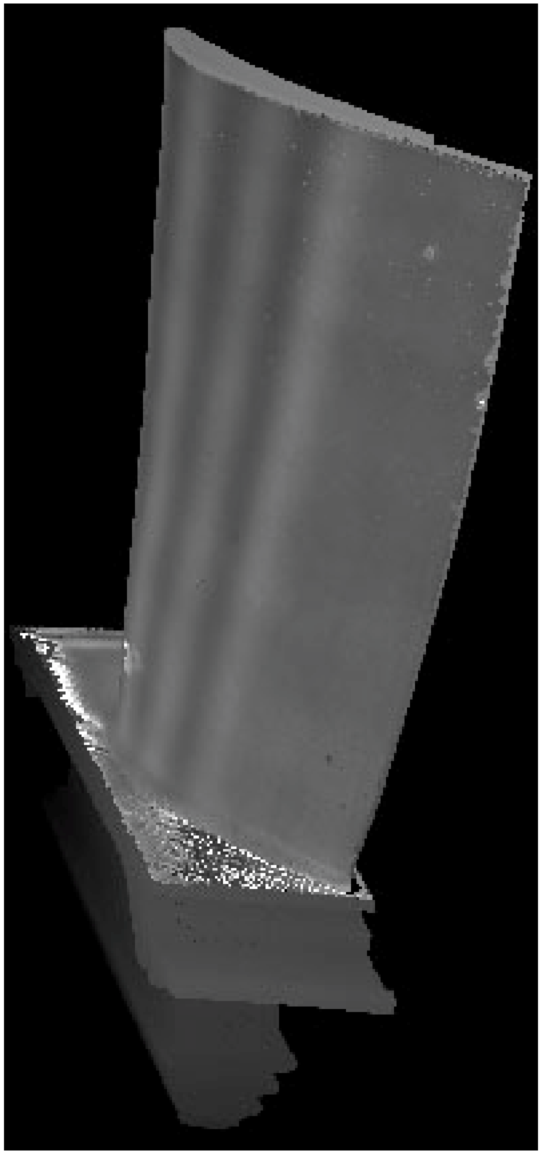


Weight is related to
flash intensity at each
surface point





Final Result: TBC Thickness on Entire Blade



All 12 NDE sub-images are seamlessly mapped onto blade surface

NDE with Low-Cost IR Camera

- Thermal imaging NDE with room-temperature, long-wavelength IR camera (bolometer):
  - Bolometers directly measure TBC surface temperature so no need for TBC surface treatment
  - Bolometers are much cheaper so reduce NDE system cost
  - Bolometers are much smaller so well suited for field applications

Task 2: Summary

- Validated thermal imaging multilayer analysis (MLA) method for NDE of entire TBC lifetime
  - Successfully evaluated TBCs from as-processed to end of life
- Developed new NDE capabilities for engine component inspection
  - Mapped MLA data on 3D engine components
  - Evaluated low-cost IR camera

Task 2: Planned FY2017 Efforts

- Thermal NDE method developments:
  - Complete modeling for translucent TBCs
  - Address curvature effect to NDE results
  - Evaluate TBCs at high-temperature conditions
- Tech transfer