Turbine Tip Clearance Issues and Optimization for Increased Power and Efficiency

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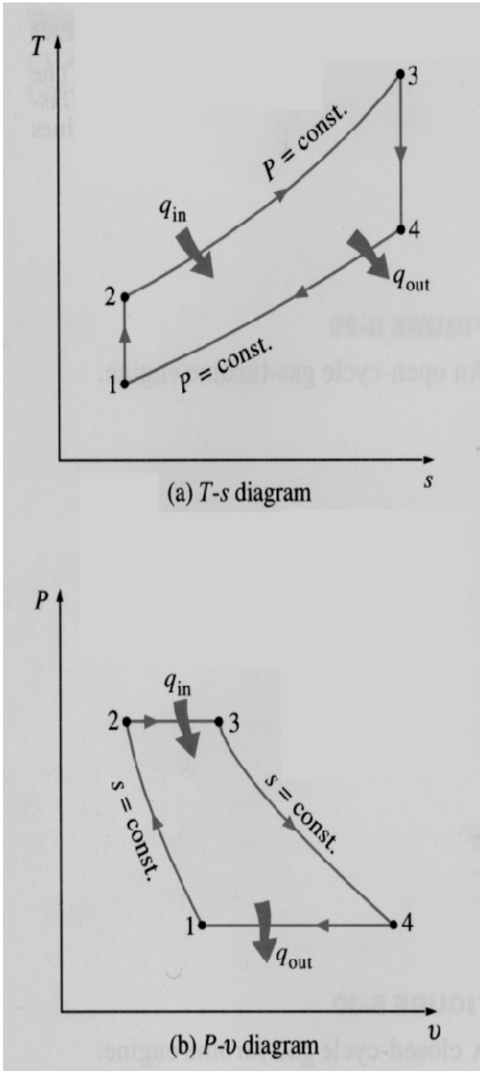
Liburdi Turbine Services Inc
www.liburdi.com

Why Does Tip Clearance Affect Efficiency ?



(a) T-s diagram

(b) P-υ diagram

Gas Turbine Brayton Cycle

$$\text{Eff} = \frac{T3 - T2}{T4 - T1} = \frac{\Delta\text{ T Combustion}}{\Delta\text{T Exhaust - Inlet}}$$

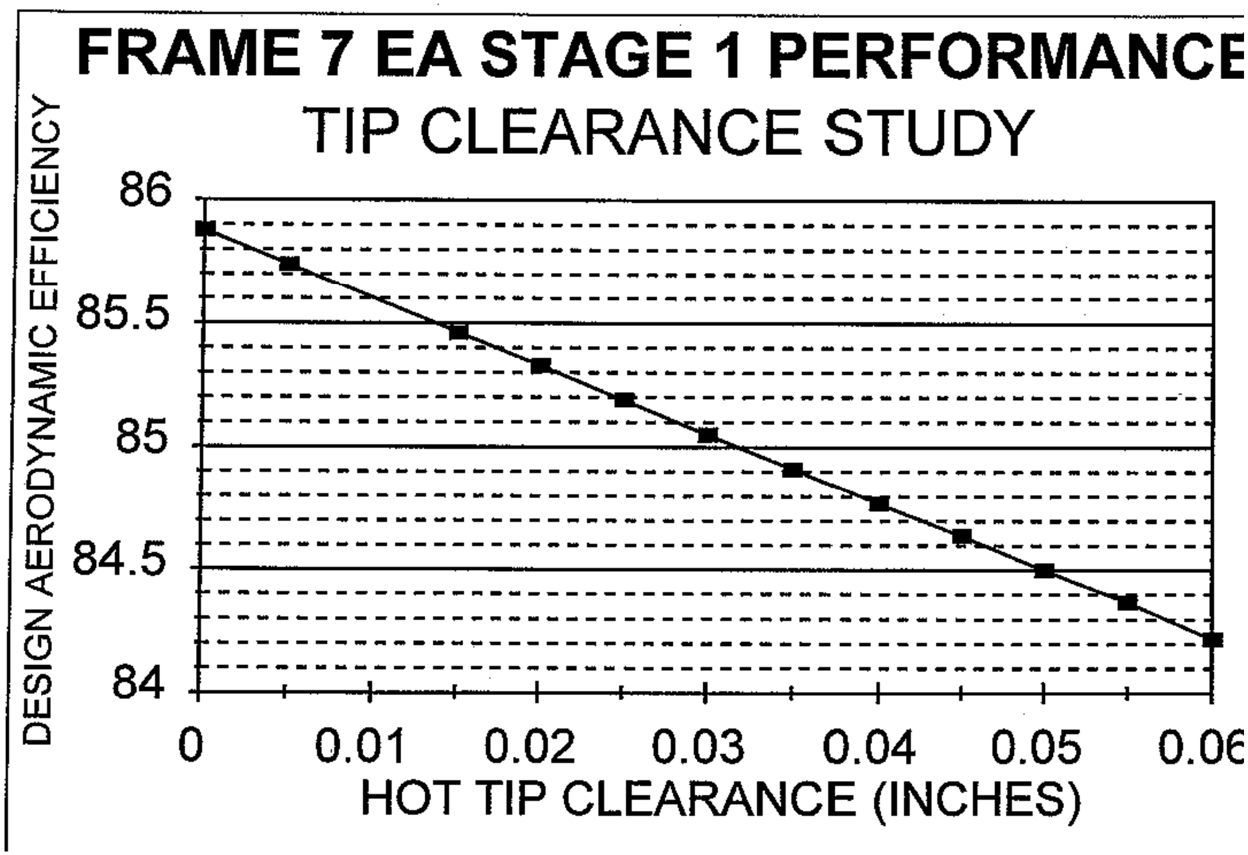
$$\text{Eff} = 1 - \frac{1}{\left[\frac{P_2}{P_1}\right]^{\frac{k-1}{k}}}$$

Efficiency is proportional to pressure drop through the turbine -- pressure losses due to leakage over blade tips means no work produced by leakage

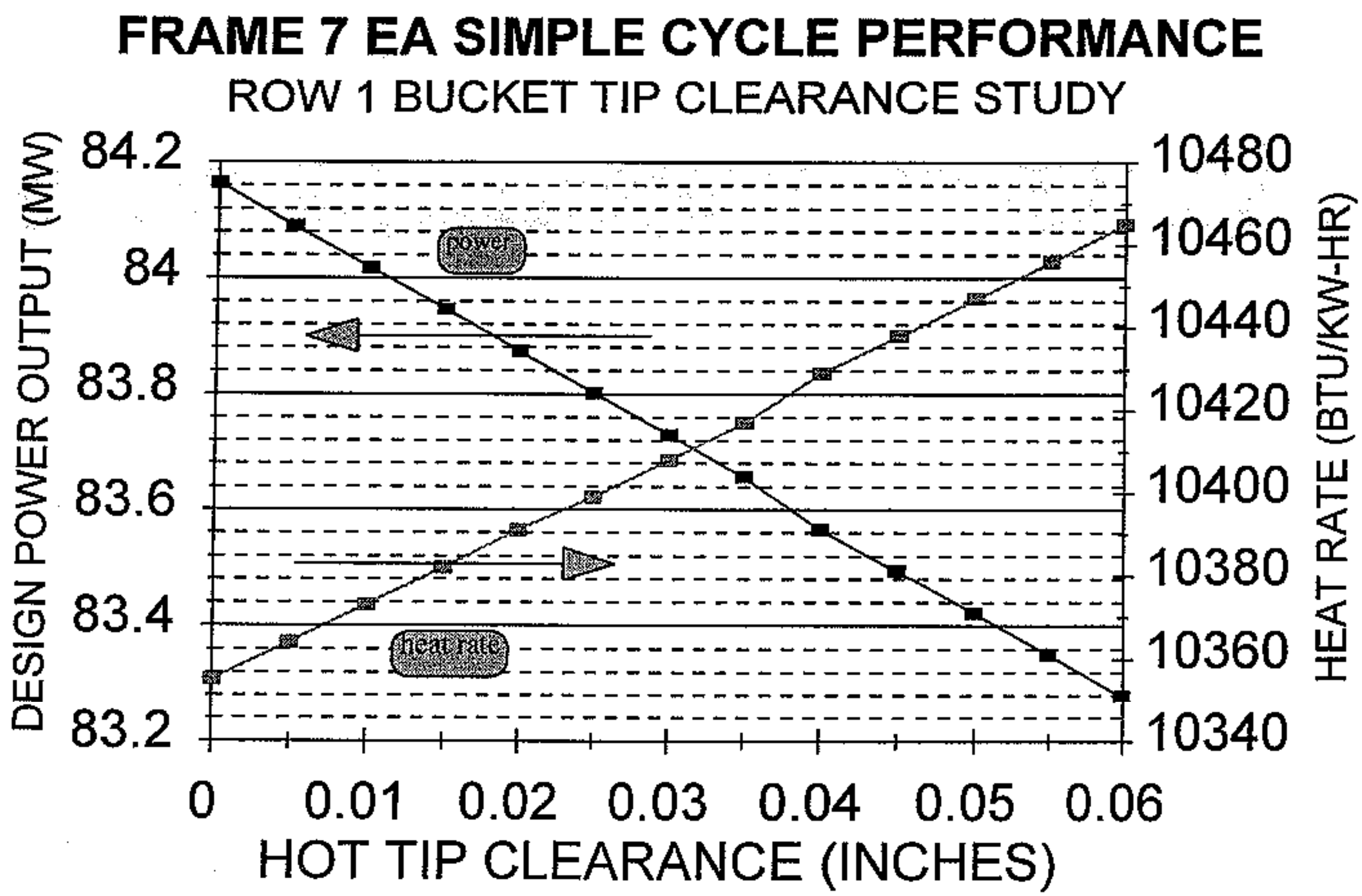
Turbine Blade Tip Clearance

- Tip Clearance between Turbine Blades and outer Shroud Blocks – is a significant design feature
- Excessive tip clearance produces efficiency and power losses
- But - Insufficient tip clearance leads to tip rub/damage
- Optimum tip clearance, for turbine blades produces maximium efficiency and power
- Example: 0.040” excessive tip clearance increase results in a 0.5% power loss – eg for a 50 MW engine results in 0.25 MW power loss
- 0.25 MW lost power is equivalent to $120,000-$240,000 losses per service interval at 2 – 4 cents per kWhr.

Example:
Engine Efficiency vs Tip Clearance



Example:
Engine Power vs Tip Clearance



Modern Advanced Engine Design

- Optimized stage 1 blade tip clearance by performing final tip height grind with blades in the rotor (achieve consistency)

- Apply an ‘engineered blade tip” of different material during stage 1 blade manufacture

- Original casting alloy is selected for high temp strength – single crystal, directionally solidified alloy

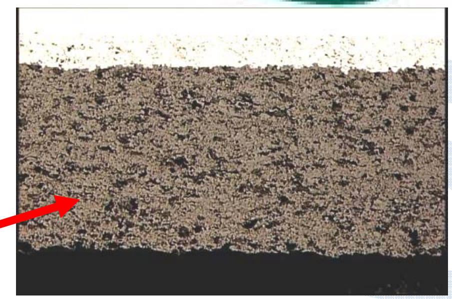
- Engineered tip incorporates a different material for superior oxidation resistance

- Engineered tip can also contain embedded abrasive particles (cBN, alumina, etc) to “grind” into abradable shrouds blocks and create optimum (minimum) clearance

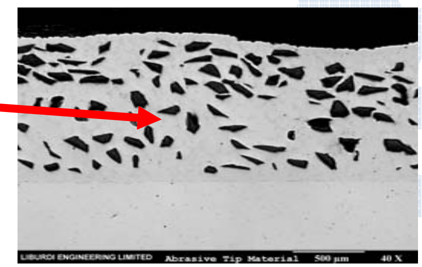
Modern Advanced Engine Design

- Example of Optimized Clearance Control – Mercury 50

- Outer shrouds with Abradable coatings



- Blade Tips - single crystal cast blades (high strength) with engineered tip of abrasive particles embedded into oxidation resistant matrix (MCrAlY like material).

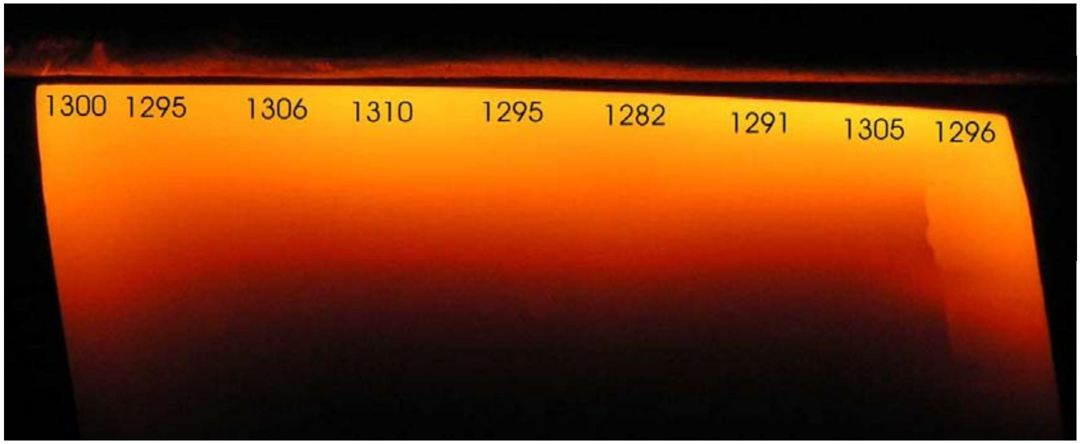


- Tip is applied as a Powder Metallurgy or Sintered pre-form material and fused to tip in vacuum furnace

Vacuum Induction Braze (VIBE) Process for Tip Repair

Special profiled braze tape applied to tip

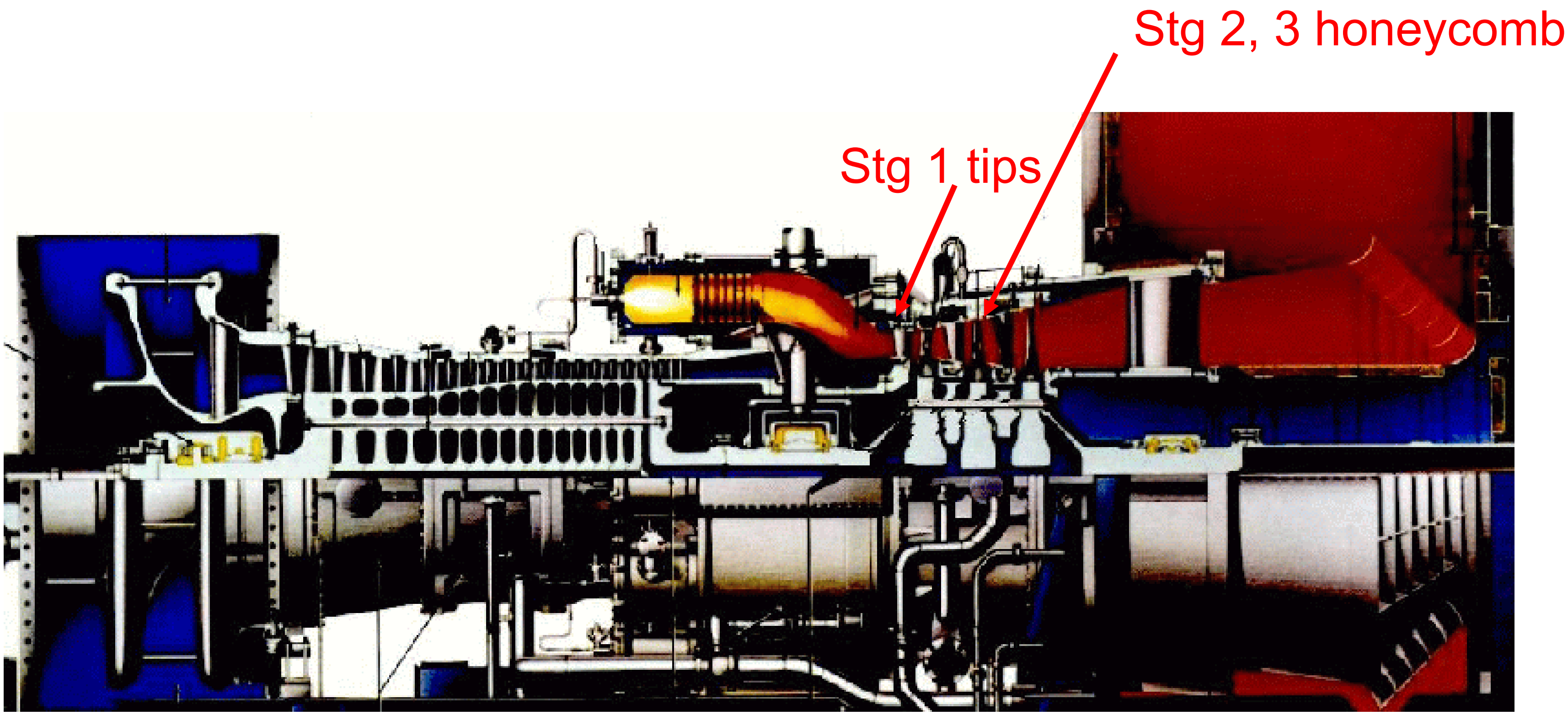
Localized heating at tip in vacuum environment



IR Pyrometry confirms that the temperature gradient is +/- 15^{o}C at tip

Example:
GE Frame 7EA Performance Upgrades

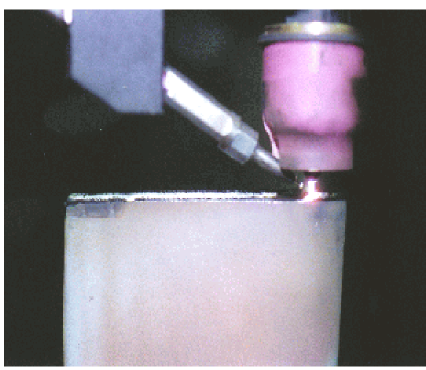
- First stage tip clearance upgrade (0.035”) for extra power +500 kW
- Stage 2, 3 honeycomb and cutter tooth seal +500 kW

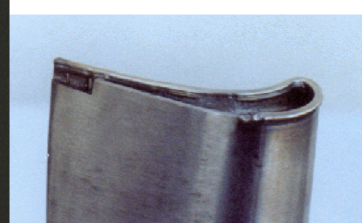


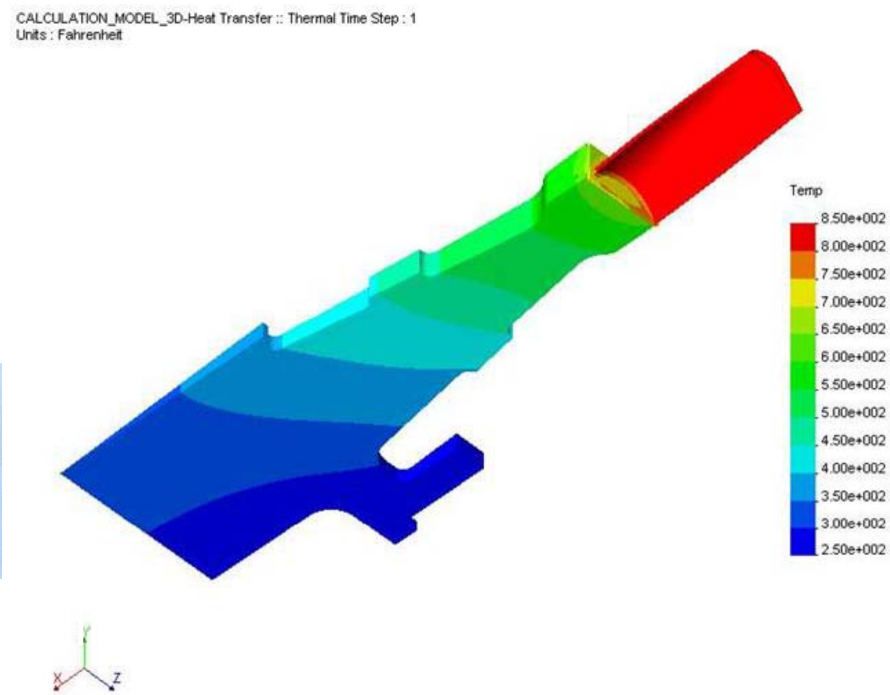
Frame 7EA Upgrade - Stage 1 Buckets

Improved Tip Clearance for Power/Efficiency

- GE Frame 7EA Stage 1 Bucket tip extension (retrofit) instead of replacing shroud blocks with low profile shroud clearance mod
  - Computer modeled for hot, cold and transient
  - Modification done at same time as repairs
  - 0.5 Mw Power increase







Optimization Part 1 - Maintain Bucket Design Tip Height

- Bucket original design tip height is often compromised by metal loss due to high temperature oxidation and/or tip rub

- This can increase tip clearance by as much as .030” - .060” beyond original design clearance

- High temperature oxidation can be prevented by applying an oxidation resistant weld alloy to the bucket tips

- Some examples follow:

Bucket Tip /tŜI·ǈI·yŎŜ Deterioration

- Bucket original design tip height is compromised by metal loss due to high temperature oxidation and/or tip rub

- Most high performance engines suffer high temperature oxidation at the tip – original alloys and conventional coatings are unable to prevent oxidation metal loss

Frame 7FA Stage 1 Bucket

Rolls-Royce RB211Stage 1 Blade

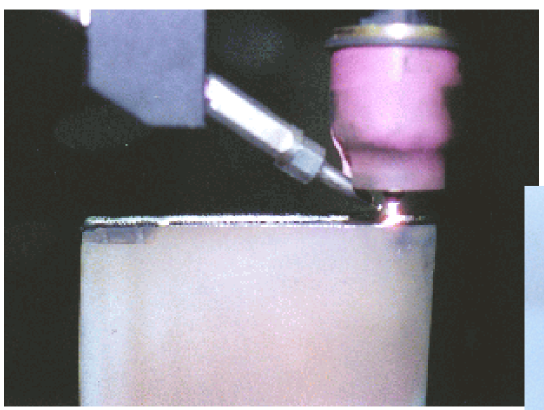
LM1600 F404 Stage 1 Blade

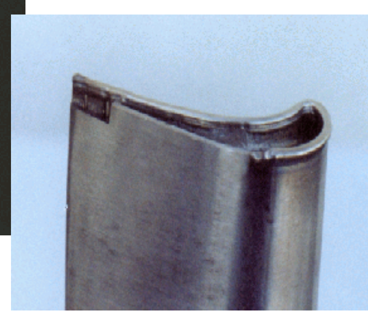
Upgrade Bucket/Blade Tips for Oxidation Resistance

- Oxidation Resistant weld alloys are available – Nickel based, with higher Aluminum content than original casting alloy

- Proven performance with L3667 Alloy – over 15 years – with IGT frame, and aeroderivative GTs – superior oxidation resistance compared to GTD111

- Weld Alloy is high strength as well as oxidation resistant – requires automated welding process to apply to tips





Frame 7FEA Stage 1 Bucket

GE LM1600 Stage 1 Blade
after 26,000 hours

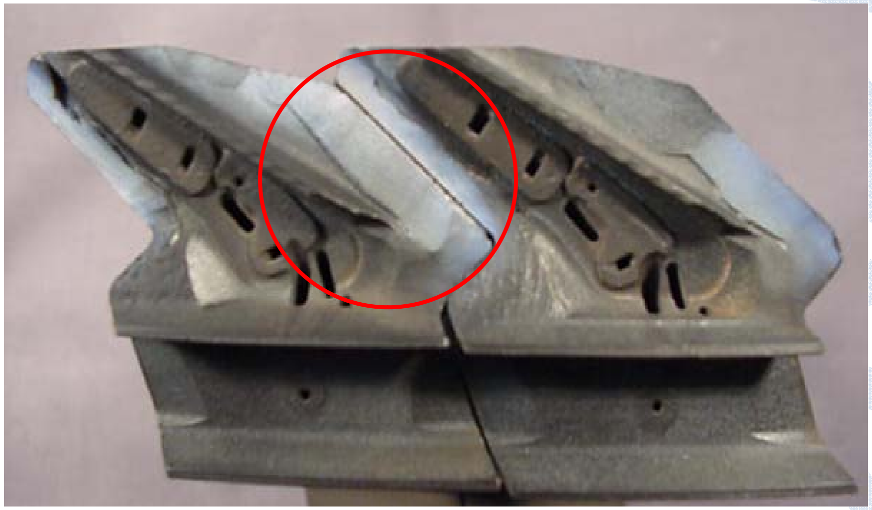
Upgrade Bucket/Blade Tips – RB211 \ Aero-derivative Experience since 1995

***L3667 Alloy* Weld**

24,000 hours service aftre repair

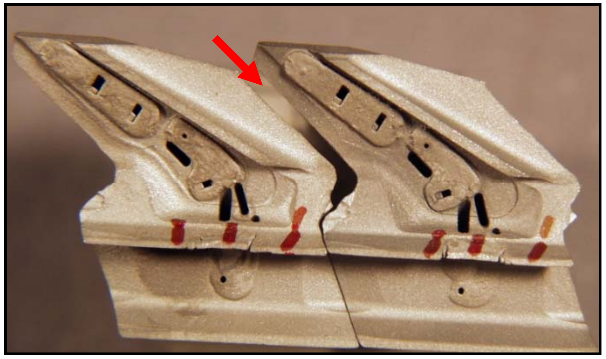
- no shroud metal loss

Sets now achieve 24,000 hours and multiple service intervals through to 100,000+ hours



New Blades 12,800 hrs service

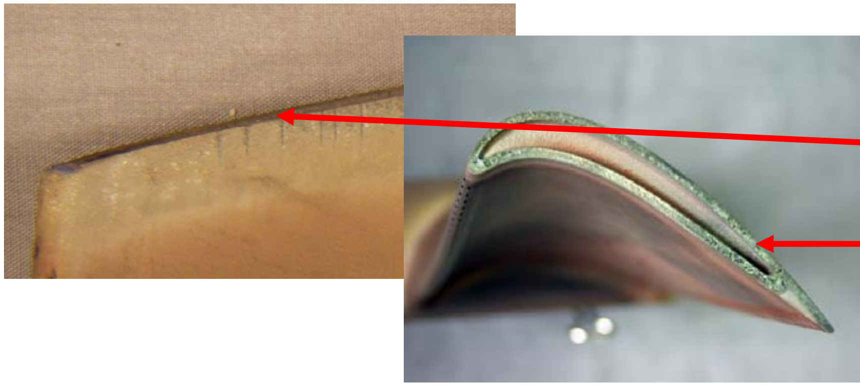
- metal loss leads to weld repair



Conventional Weld after 13,000 hrs service

- conventional weld repair - extensive metal loss

Siemens V84.3A1 "F" Class Single Crystal Tip Welds



- Single Crystal Alloy
- Cracking at blades tip
- Oxidation burning at tip

- Automated Welding with Oxidation Resistant L3667 weld metal

Example - GE Frame 7F! Stage 1 Bucket

Natural gas fuel, 25,000h total service hours, 500 starts since repair

Repair Service A –
Using conventional weld alloy

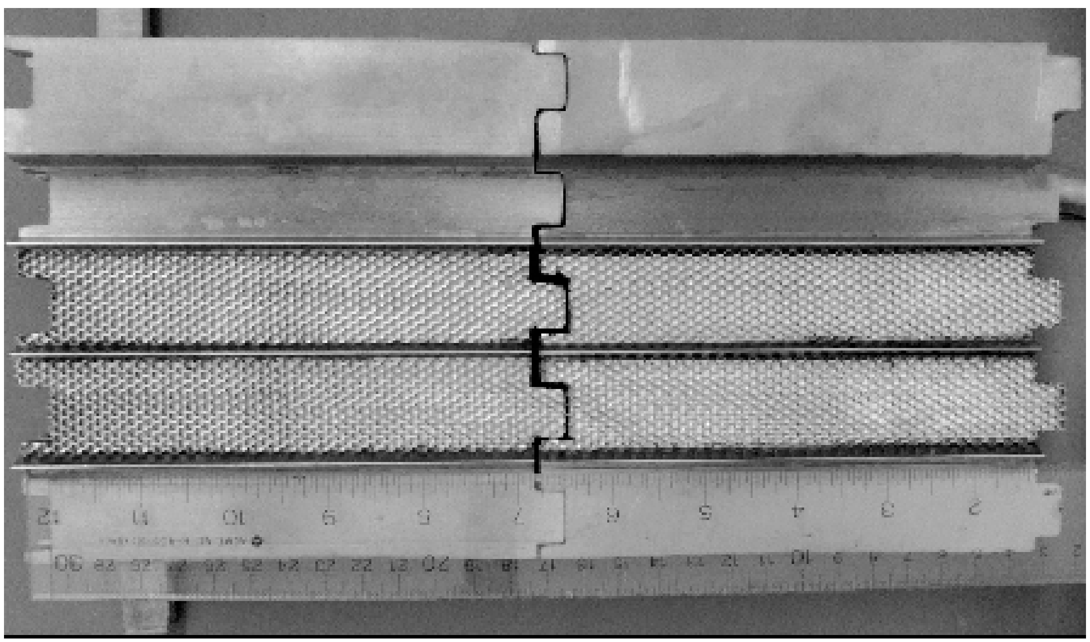
Repair Service B–
Total tip replacement
Using conventional weld alloy

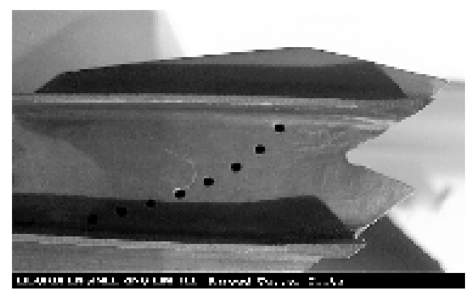
Repair Service L–
Using L3667 oxidation resistant weld alloy

GE Frame Performance Upgrades - Stage 2

Frame 7EA Stage 2 Upgrade for Power/efficiency

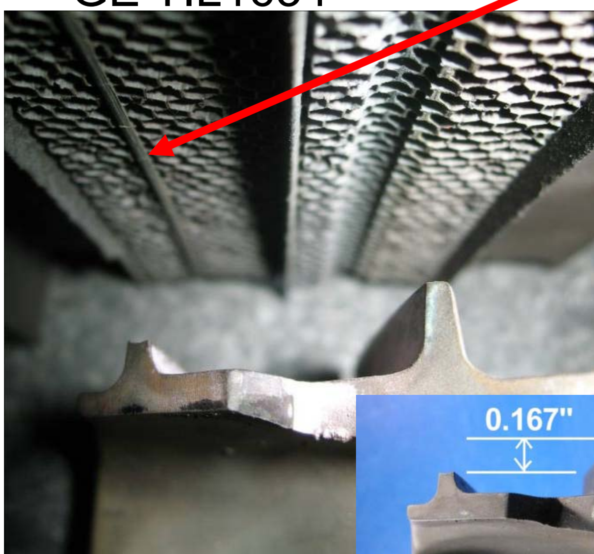
- Honeycomb seal mod to outer shroud blocks
- PW694 welded cutter teeth retrofit to buckets
- Applied at time of repairs
- 0.5 Mw Power increase
- **Existing Shrouds and Buckets upgrade as retrofit upgrades**

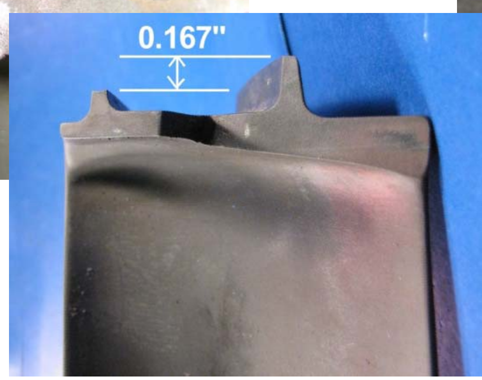


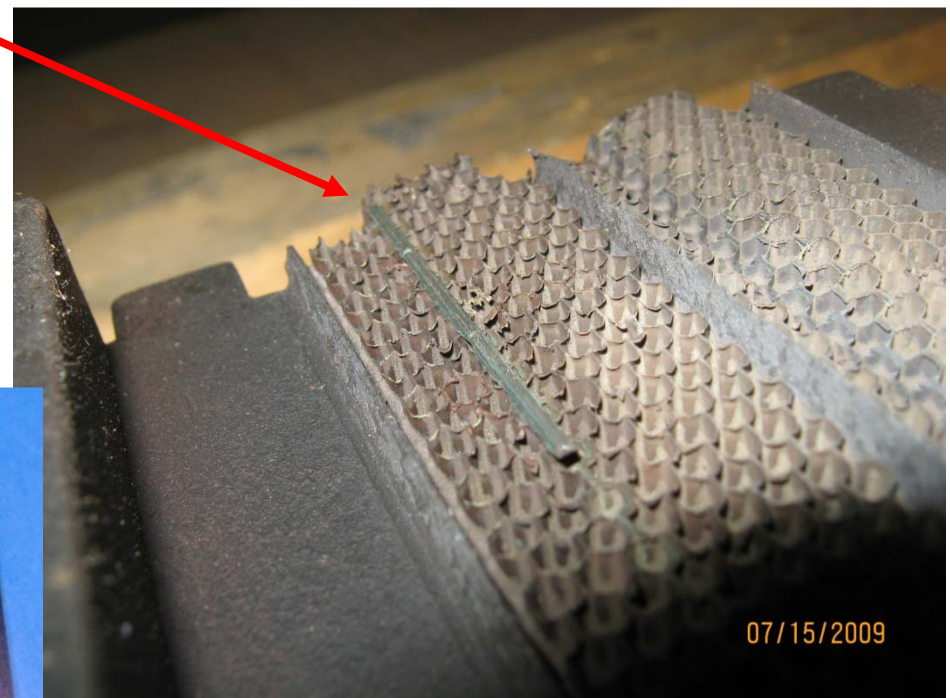


Honeycomb Seal – Cutter Tooth Bucket Rails

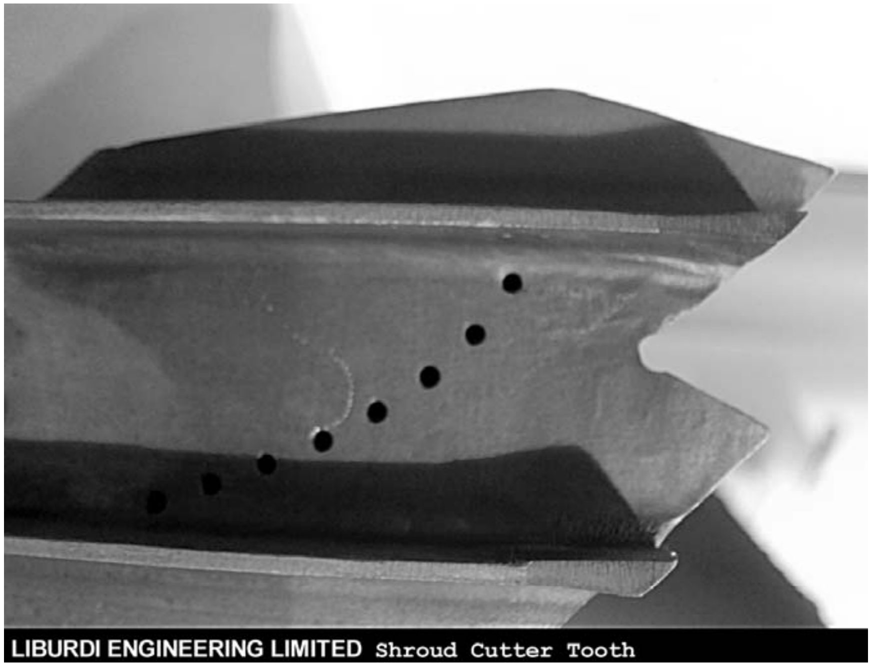
- This upgrade has been offered since mid 1990s
- There are some considerations with regard to the shroud rails and cutter tooth design.
- Original equipment cutter tooth is cast into the parts as-new – is therefore the same nickel based alloy as the bucket
- Friction between the rail/cutter tooth can result in high temperatures , transfer of rail material to the honeycomb, and rail disintegration per – GE TIL1634

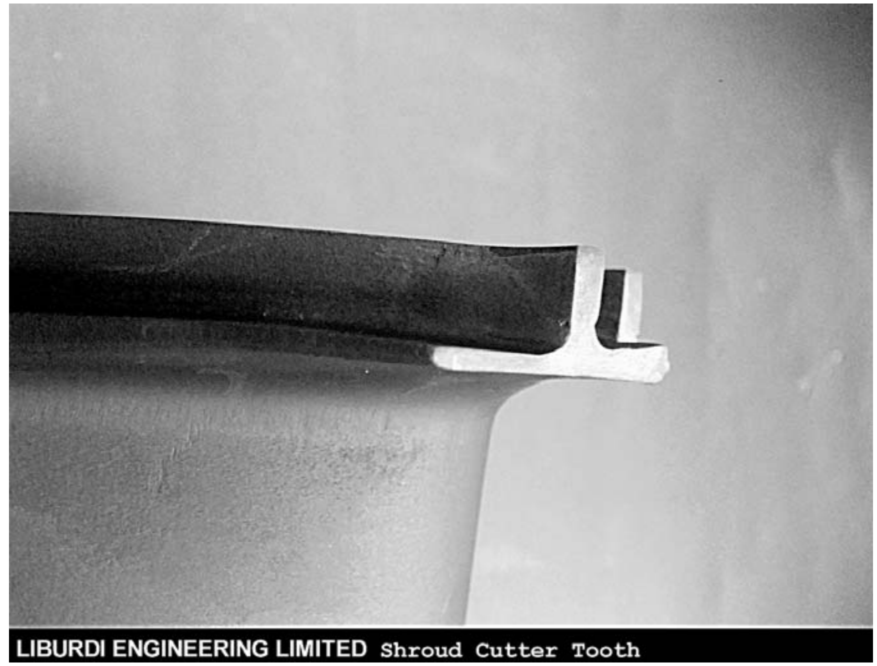






Advanced Cutter Design

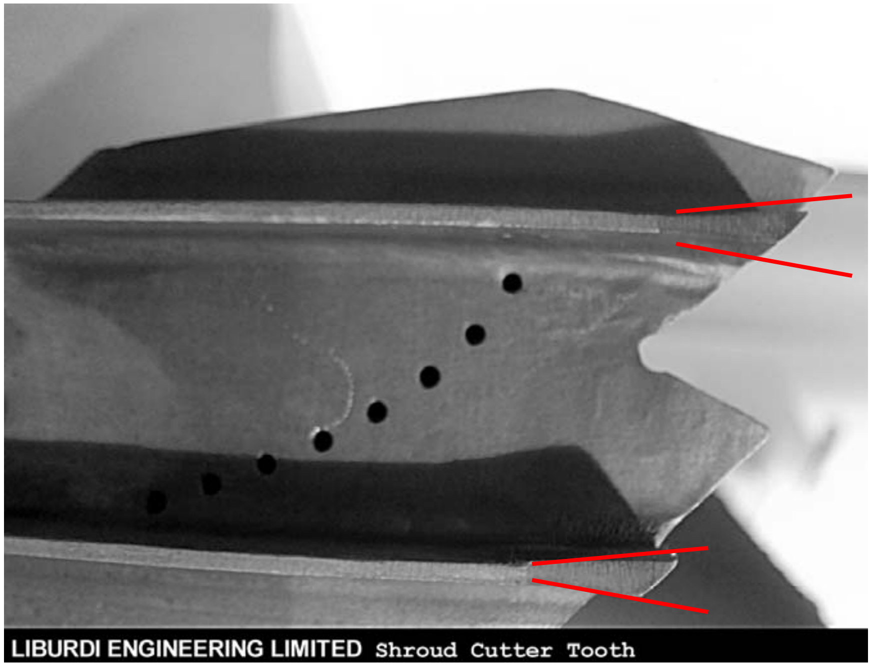


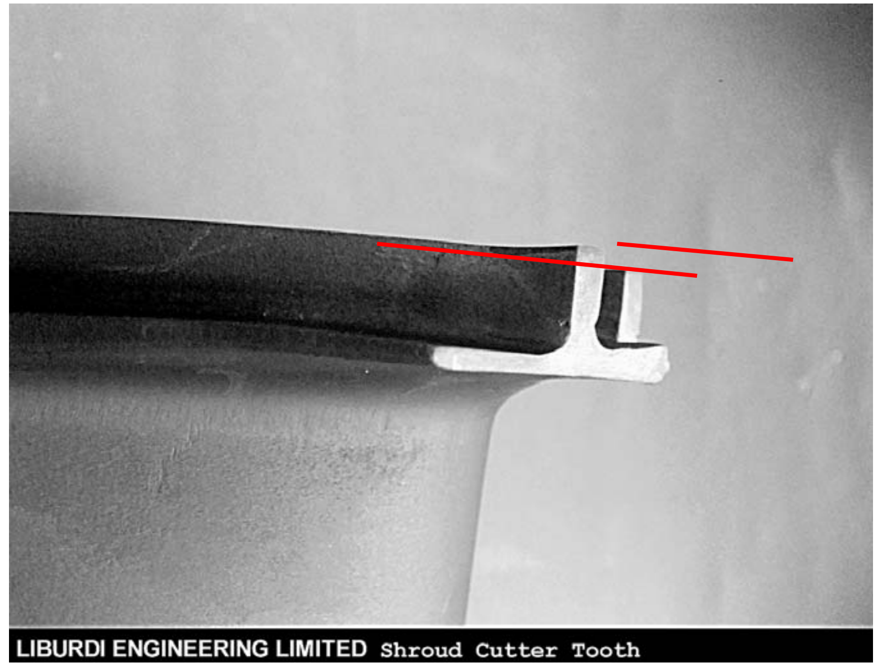


•**Advantages of Advanced Cutter Design**

- Three Dimensional cutter – incremental width and height compared to the original rail
- Provides clearance between honeycomb and rail on both sides and top surfaces
- Avoid rail contact in all <u>three</u> surfaces – pre-grooving clearances on top and sides
- Stellite hardface machining alloy used for superior cutting
- Only one quarter of buckets have cutter applied – to cut a path for all buckets
- Applied as a retrofit – operator retains original parts

Advanced Cutter Design





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GE “F” Class Repair Technologies
Stage 2 & 3 Frame 7FA Shroud Restoration

- Restore z-notch - hardface weld PWA64 alloy
- High Strength LPM powder metallurgy repair for crack and impact damage
- Re-Profile to reduce stress concentrations and balance shroud

* Apply abrasive to rails on
   to prevent rubbing after

   Creep deflection

Optimization Part 2 - Tailored Shroud Block Heights - Abradable Shroud Coatings

Mature Engines suffer distorion of turbine casings over time

- Casing radial dimensions, and tip clearances, tighter at split lines due to rigidity of bolting flanges
- Simply restoring bucket tip heights is defeated by shroud rubs incurred due to out-of-round casings
- Solution is to tailor shroud block thicknesses to accommodate casing distortion, and restore close-to-cylindrical arc for turbine blades
-

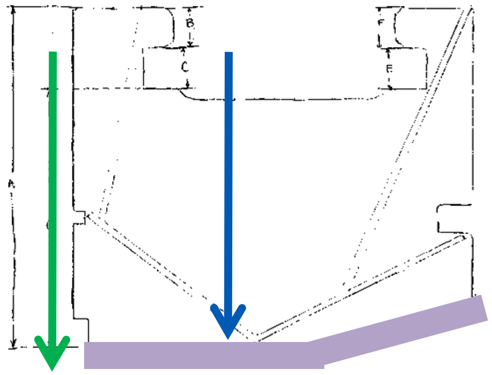
Case Study - Frame 7EA
Tailored Shroud Block Height

- Common for diameters at spilt line to pull inward over time
- Shroud blocks at split line tend to be tight clearance – shroud rubs and bucket **rubs are apparent**
- Shroud blocks at vertical TDC and BDC are not rubbed – have **excessive tip clearance**
- Inconsistent tip clearance around 360 deg –

Solution: Tailor the shroud ID dimensions to accommodate ovality of the case and hook fit-ups of the shrouds – achieve consistent radius for rotor bucket tips

Modeling of Engine Distortion and Tip Clearance Adjustment

- Model Stage 1 bladed disc assembly and outer shroud block positions – for cold dimensions, and for at-temperature change in dimensions
- Take six point circumferential measurements of target engine – determine vertical and horizontal
- Determine 360 degree distortion variation in target engine case
- apply target dimensions to model – determine distribution of shroud block radial adjustments

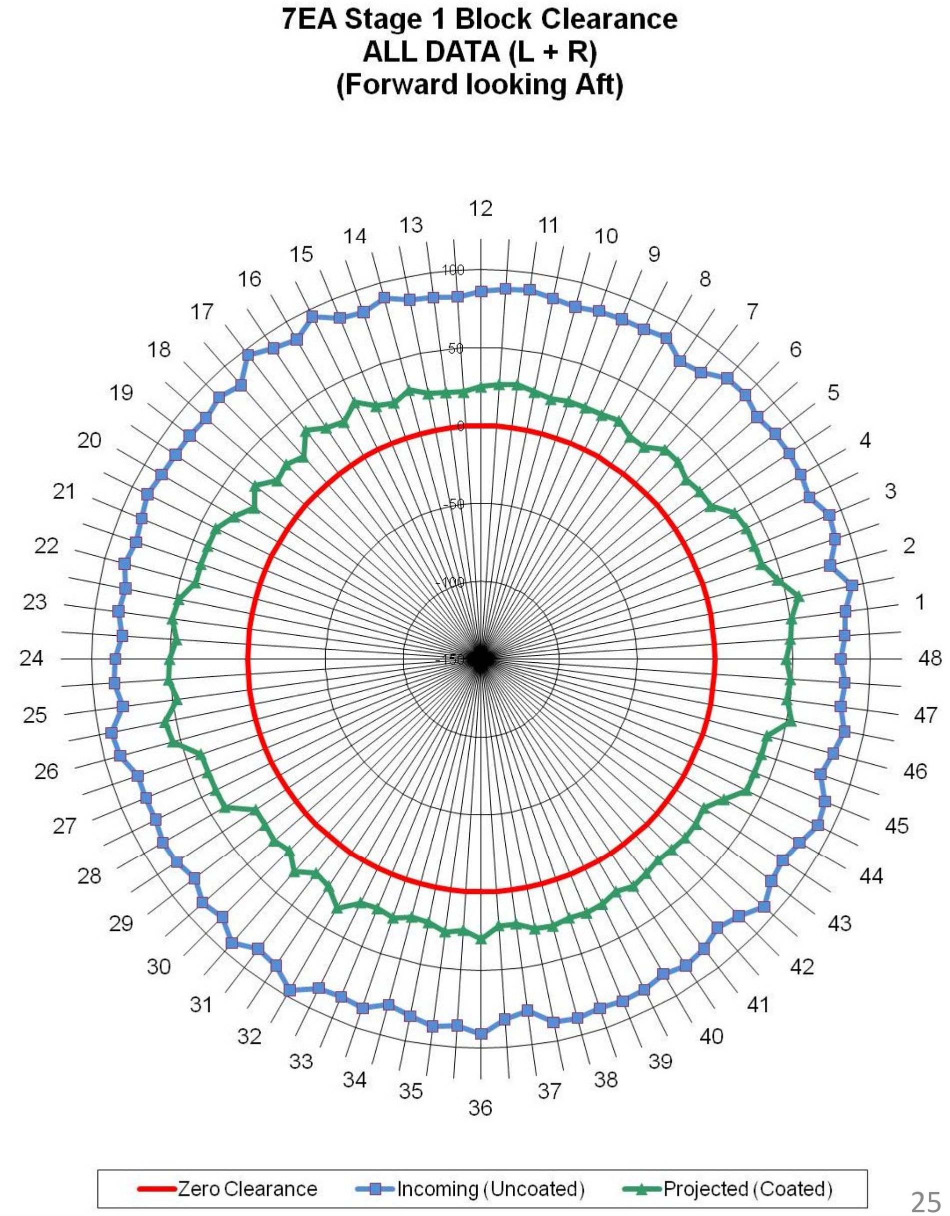


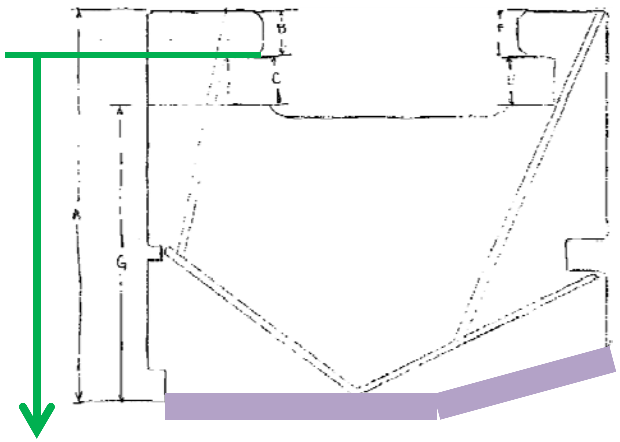
Incoming Shroud radial dimensions
Referenced to hook fits
after coating removal – Blue

Target shroud dimensions
Post-coating – Green

Net difference is the
Target thickness of the coating

Zero clearance - Red

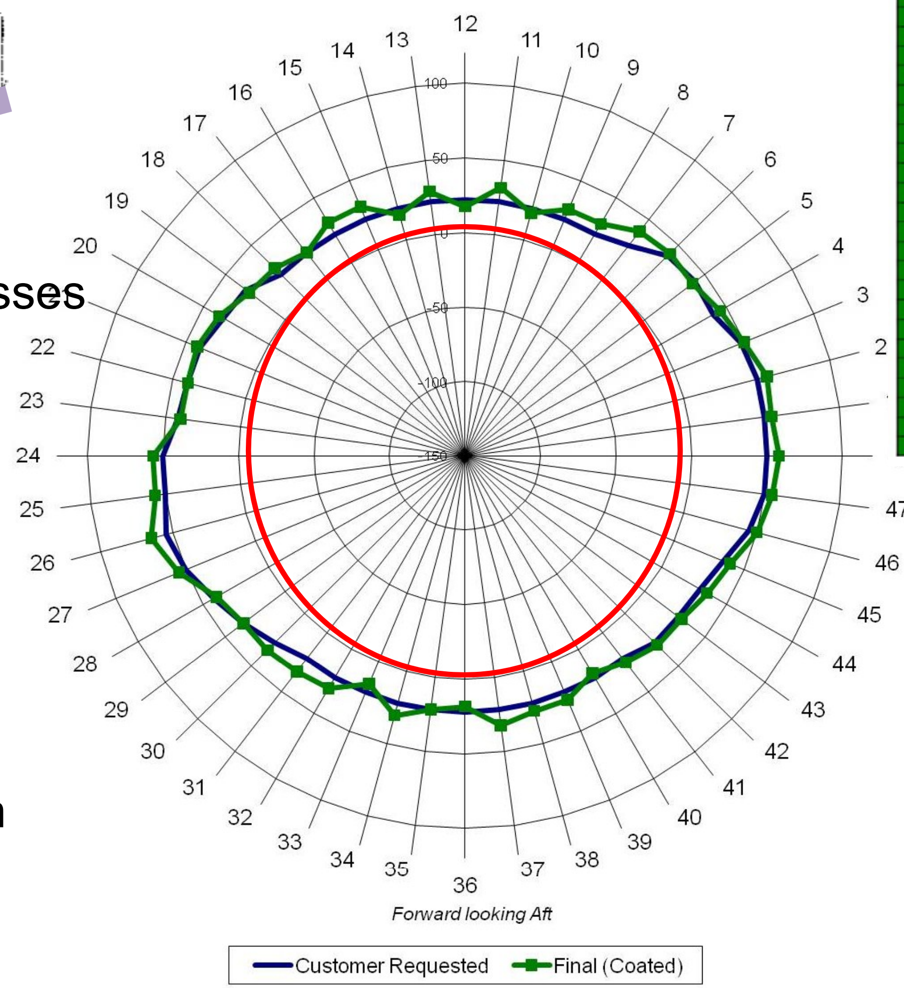




Required Thermal Spray
Abradable coating thicknesses

Target shroud dimensions
Post-coating – Blue

Actual achieved dimension
post-coating - Green



FINAL

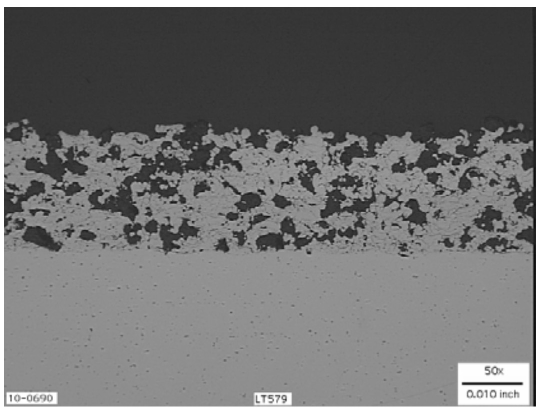
Segment #	G + C 0.00in ±0.000in	Segment #	G + C 0.00in ±0.000in
1	5.195	25	5.192
2	5.192	26	5.184
3	5.227	27	5.221
4	5.230	28	5.217
5	5.221	29	5.220
6	5.218	30	5.232
7	5.234	31	5.216
8	5.219	32	5.219
9	5.220	33	5.233
10	5.230	34	5.219
11	5.218	35	5.227
12	5.232	36	5.231
13	5.220	37	5.217
14	5.232	38	5.222
15	5.218	39	5.222
16	5.218	40	5.230
17	5.227	41	5.232
18	5.221	42	5.233
19	5.233	43	5.219
20	5.225	44	5.221
21	5.228	45	5.222
22	5.220	46	5.223
23	5.193	47	5.194
24	5.193	48	5.191

<u>Abradable</u> MCrAlY Shroud Coating

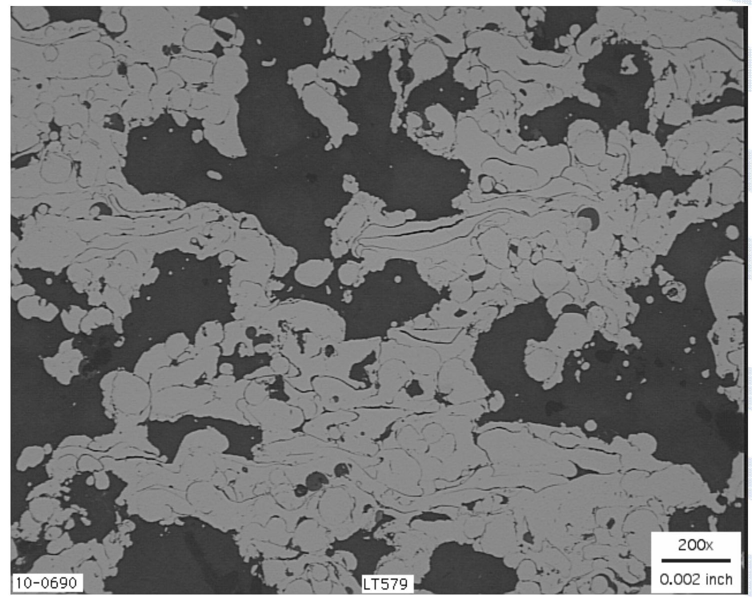
- Earlier Shroud block coatings were dense MCrAlY or ceramic TBC coatings - both were not truly abradable, and could cause metal loss to blade tips due to rub and friction
- New generation of shroud coatings are designed to be abradable (friable, sacrificial during a rub, but still need to be oxidation resistant)
- APS applied, high porosity TBCs can be used for internally cooled blocks (F class) but not appropriate for E class – too hard and no cooling benefit.
- APS applied MCrAlY, high porosity top coat is used for E class un-cooled blocks – abradable and oxidation resistant

Abradable MCrAlY Shroud Coating

- Three-layer coating includes dense seal-coat for block protection
- MCrAlY bond coat for oxidation resistance, adhesion
- Top coat Porosity levels 25% - 35% achieved with polyester sacrificial fill

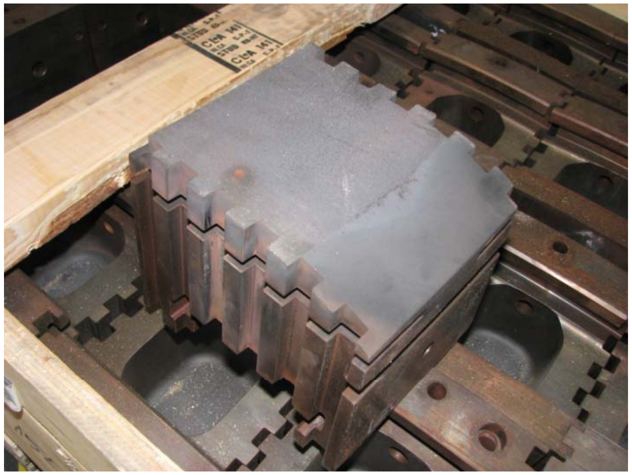


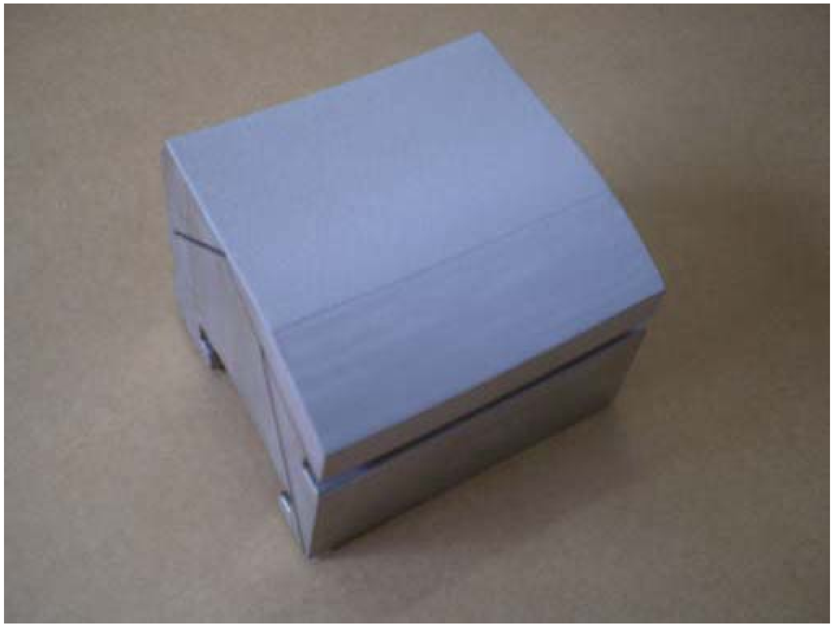
Typical top coat microstructure as viewed at 50X.

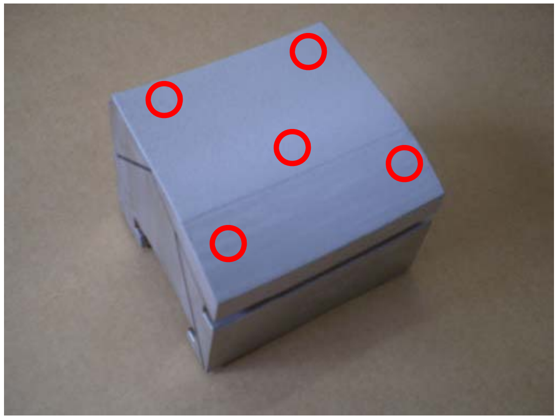


ABRADABLE TOP COAT MICROSTRUCTURE				
25% - 35%	Porosity	33.91% via Image Analysis	Accept	4 Random Areas
	Uniformity	Uniform Distribution	Accept	4 Random Areas

<u>Abradable</u> MCrAlY Shroud Coating







Test locations – adhesion bond, thickness uniformity, porosity

Liburdi Group of Companies

- *Liburdi Engineering Ltd*
- *Liburdi Turbine Services Inc*
- *Liburdi Automation Inc*
- *Liburdi Dimetrics Corp*

Dundas, Ontario Canada

Stoney Creek, Ontario, Canada

- *Dundas, Ontario*
- *Mooresville, North Carolina*
- *Amsterdam*
- *St Petersburg, Russia*

Mooresville, NC, USA