Design of the LM6000 Gas Turbine Models

imagination at work

LM6000 Module Derivation

Module/component	LM6000-PC/PD/PF	-PG/PH
• Low pressure compressor	CF6-50, LM5000	CF6-50, LM5000
• High pressure compressor	CF6-80C2	CF6-80C2
• Standard combustion system	CF6-80C2, LM5000	LMS100
• DLE combustion system	New configuration	LMS100
• High pressure turbine	CF6-80C2	CF6-80E
• Low pressure turbine	CF6-80C2, CF6-80E	LM6000-PC
• VIGV, front frame, rear frame	New configuration	LM6000-PC

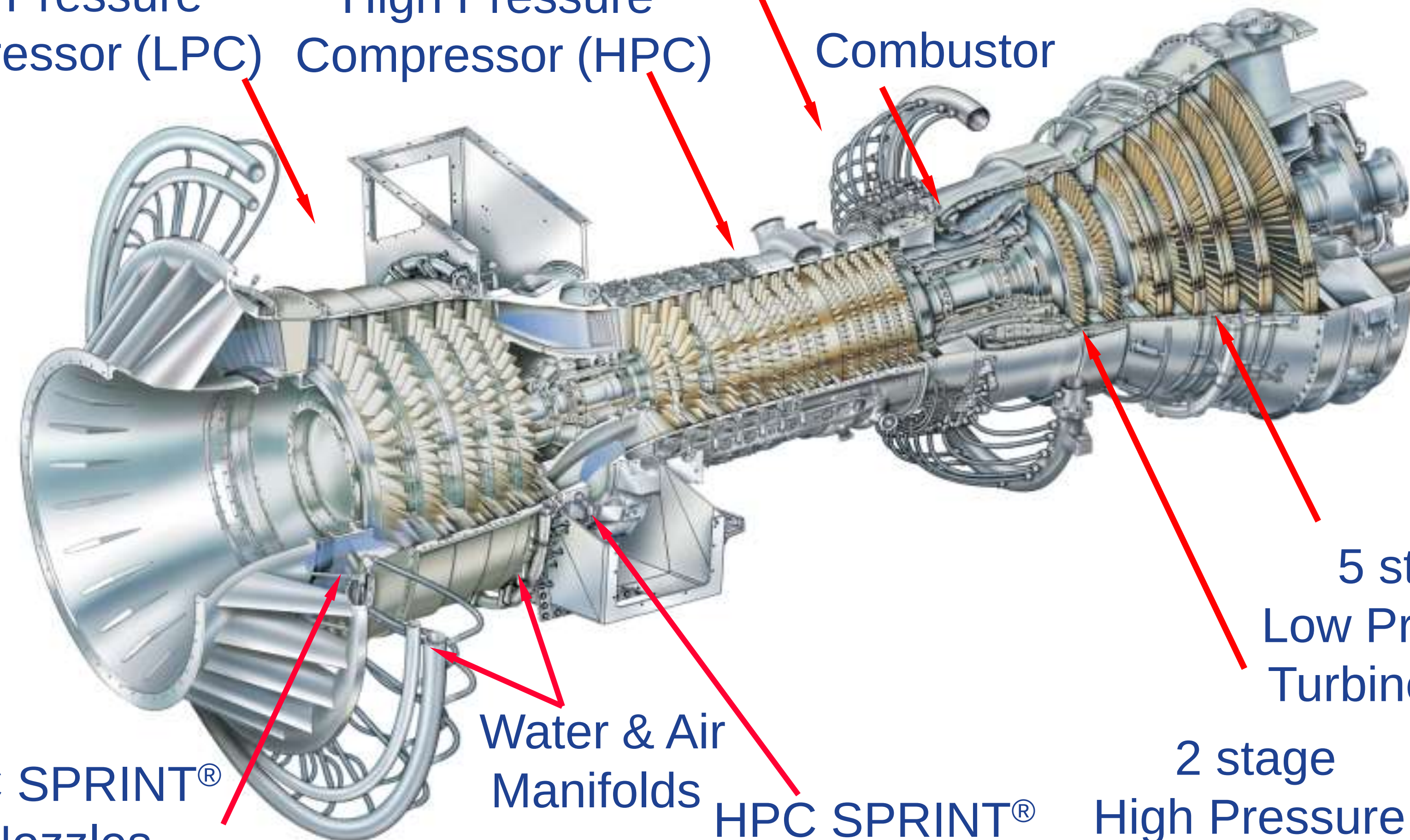
Description

5 stage
Low Pressure
Compressor (LPC)

14 stage
High Pressure
Compressor (HPC)

Fuel Manifold

Combustor



5 stage
Low Pressure
Turbine (LPT)

Water & Air
Manifolds

LPC SPRINT®
Nozzles
PC/PD/PF/PG/PH

HPC SPRINT®
Nozzles
(PC/PD/PF only)

2 stage
High Pressure
Turbine (HPT)

PG Engine Modifications

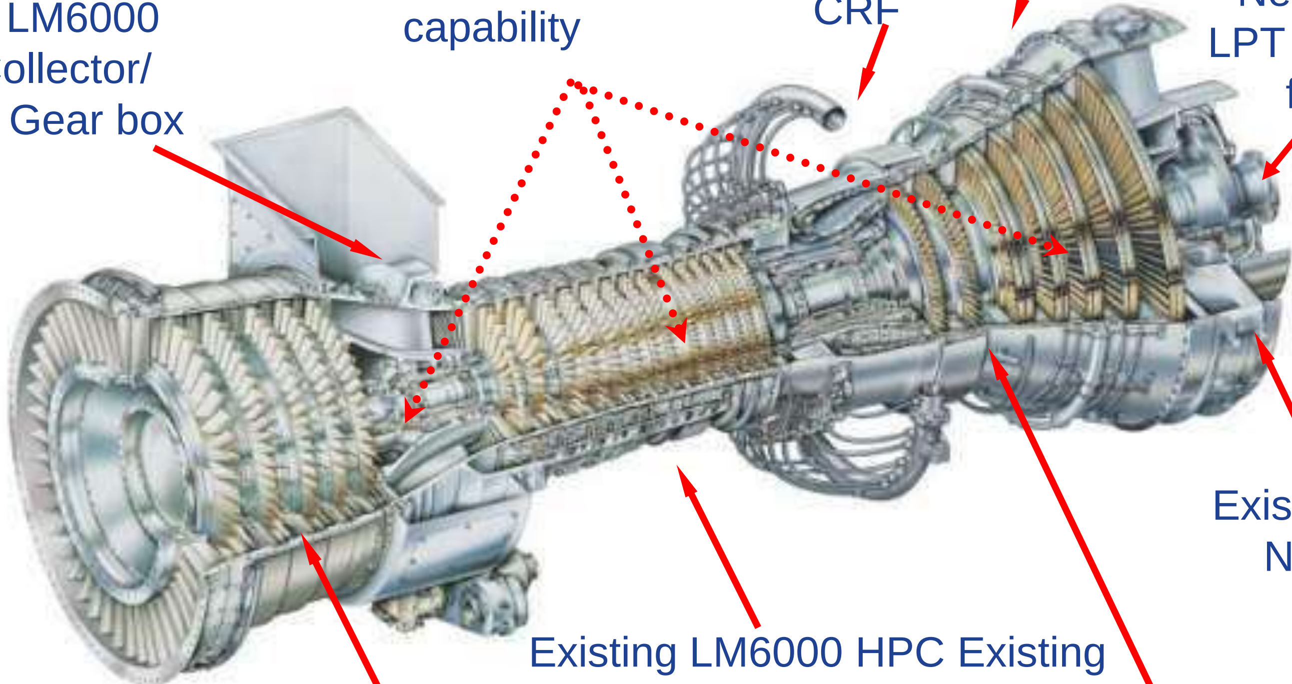
Improved LM6000 Stator
New Case Material
LPT airfoils optimized
for efficiency

LP Shaft
Spline Improvements
for higher torque
capability

Improved
SAC
Combustor &
CRF

Improved LM6000 rotor
New disk material
LPT airfoils optimized
for efficiency

Existing LM6000
CFF / Collector/
VBV, and Gear box



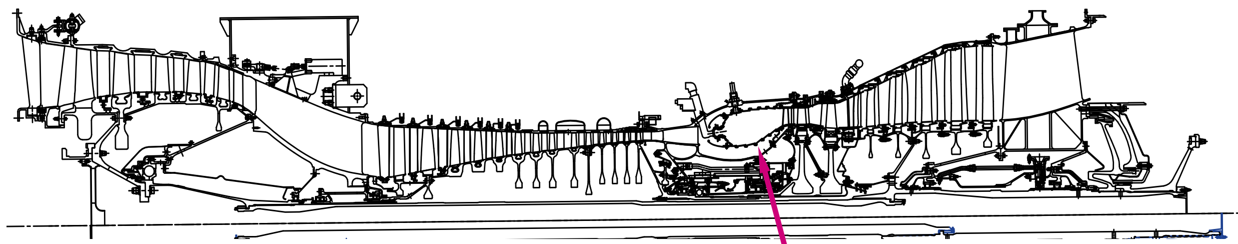
Existing LM6000 TRF
New 7R bearing

Existing LM6000 Booster
@ 3930 RPM
Premium Material Disks/Shafts

Existing LM6000 HPC Existing
Blades and Vanes
Stage11 from CF6-80E
New Spool/Disk and Seal Materials
Case Bleed Modifications

Boltless Design HPT
Disks and IS seal (R104)
New Airfoils

Gas Turbine Cross Sections

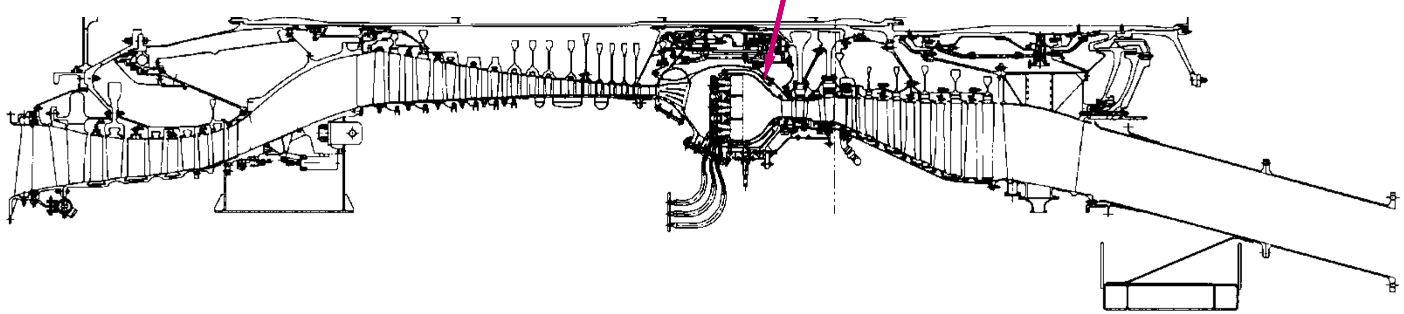


LM6000-PA

SAC

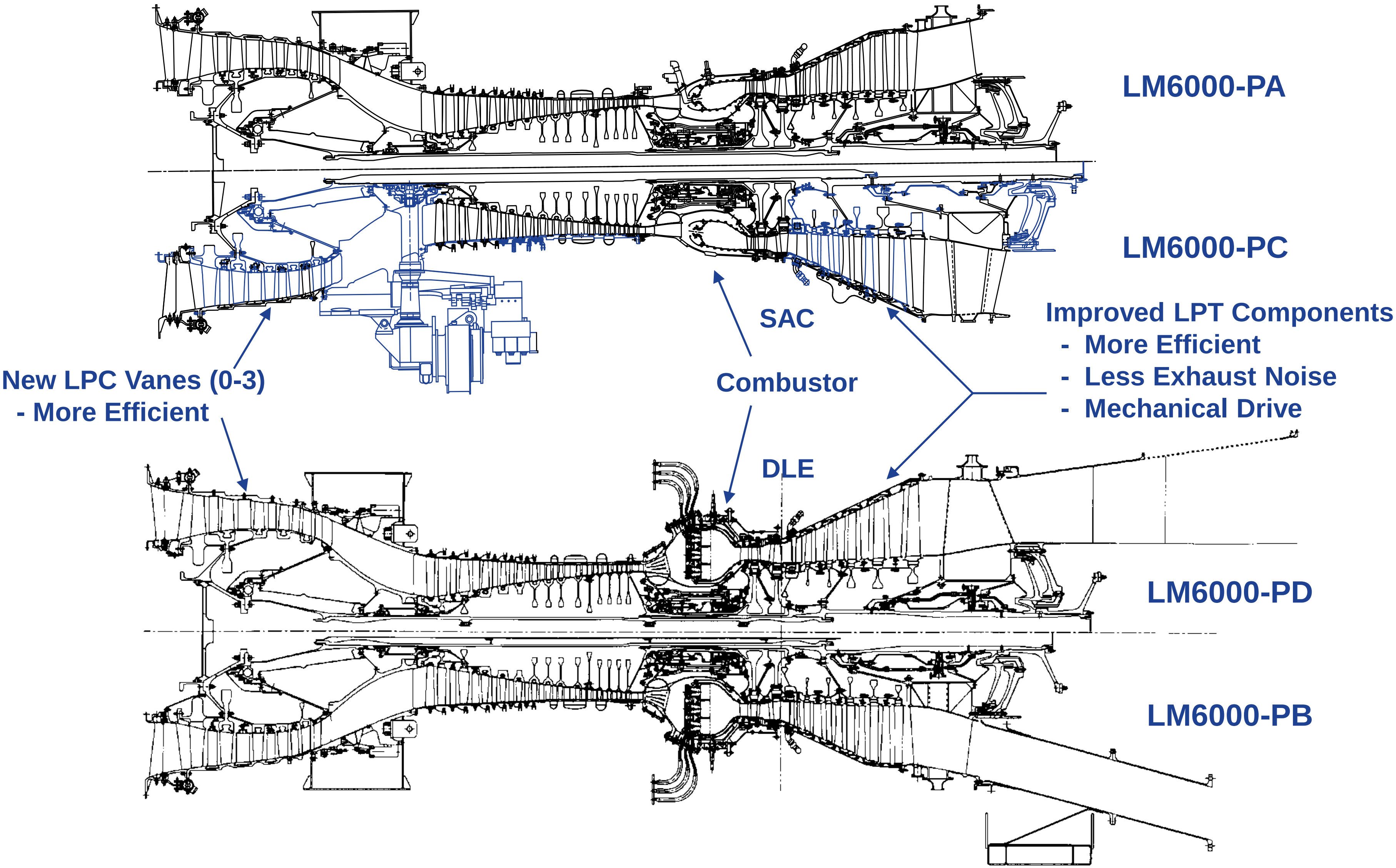
Combustor

DLE



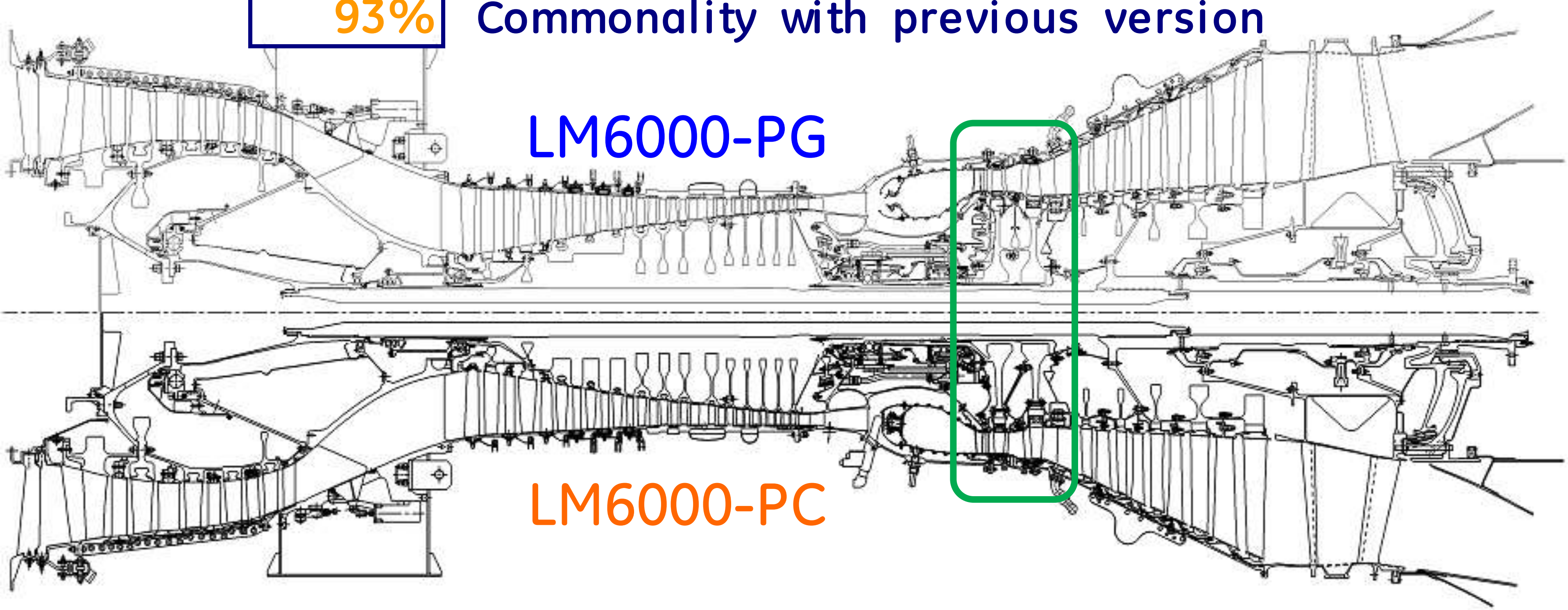
LM6000-PB

Gas Turbine Cross Sections



PG to PC ➔ >93% commonality

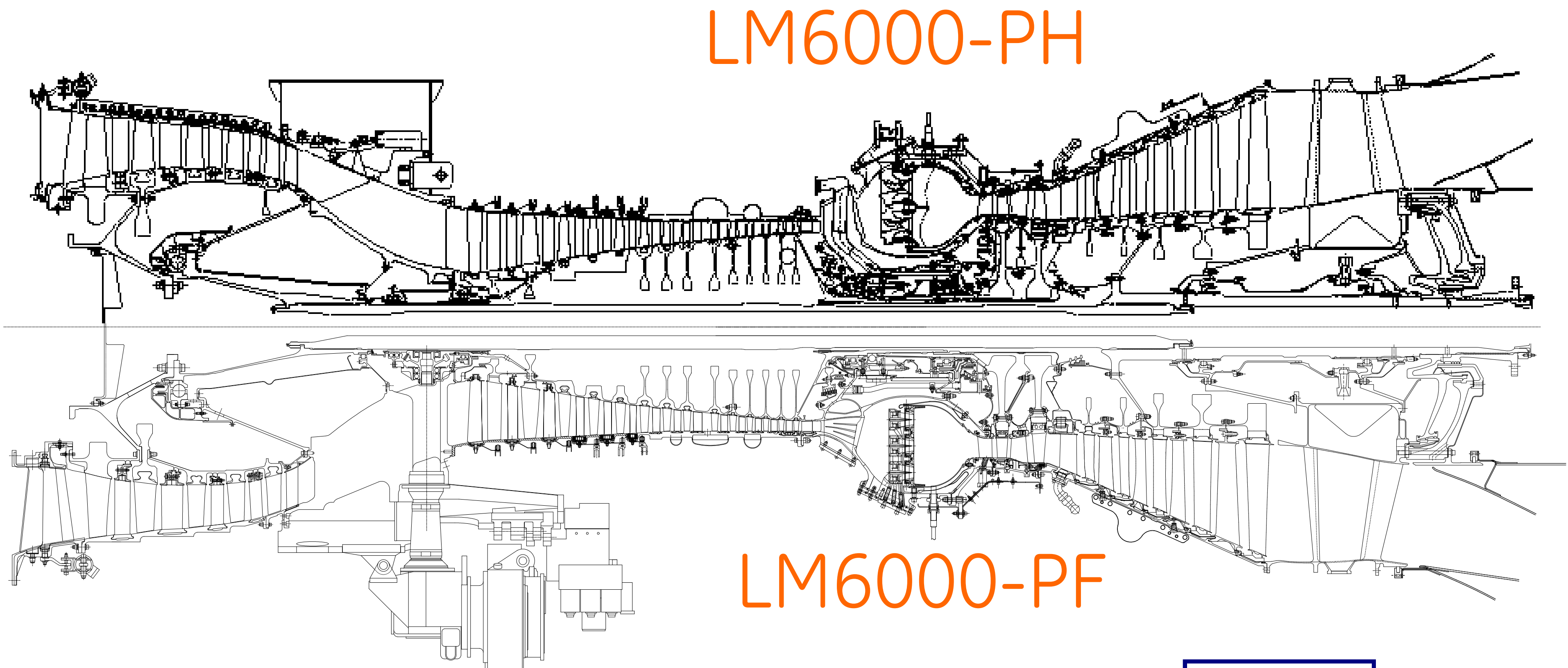
20,088	Engine level parts to Assemble
2,477	Part numbers
165	New part numbers for -PG
93%	Commonality with previous version



Maintaining the heritage of a well proven product

One of the significant changes is in the high pressure turbine

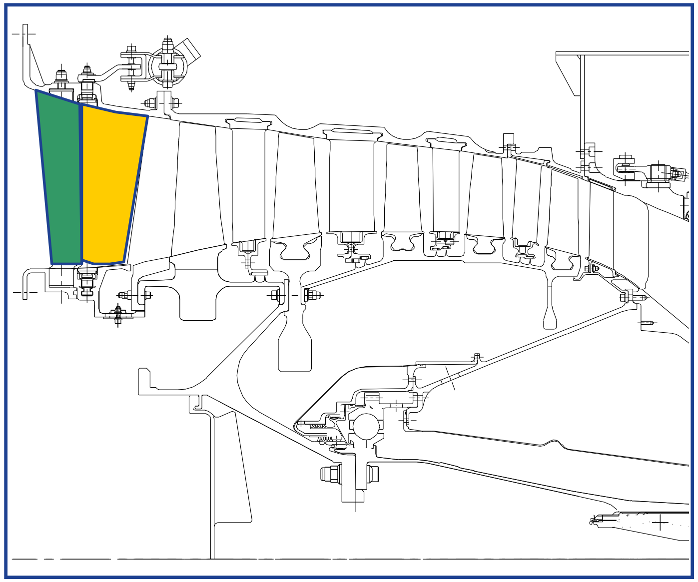
Maximize similarity between –PF and -PH

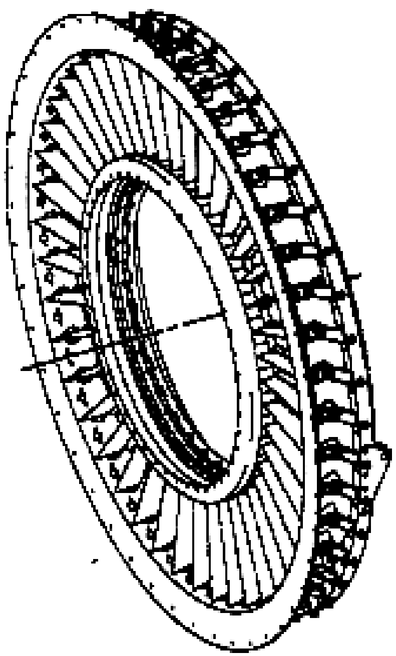


Engine level parts to Assemble	21,425
Part numbers	2,808
New part numbers for -PH	251
Commonality with previous version	91%

imagination at work

Variable Inlet Guide Vanes (VIGV)





Same for PC and PG

- ***Standard for mechanical drive***
- ***Optional for power gen on -PC only***

- Part of low pressure compressor module

- Regulates inlet airflow for optimum compressor loading and enhanced hot day power & part-load efficiency

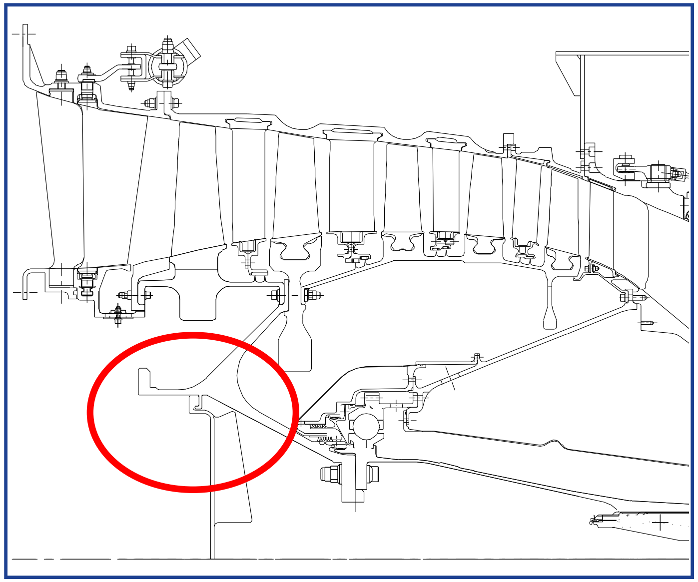
- 43 articulated vanes - fixed leading edge and movable trailing edge

- Hydraulically actuated unison ring with 2 actuators

- Inlet airflow interface

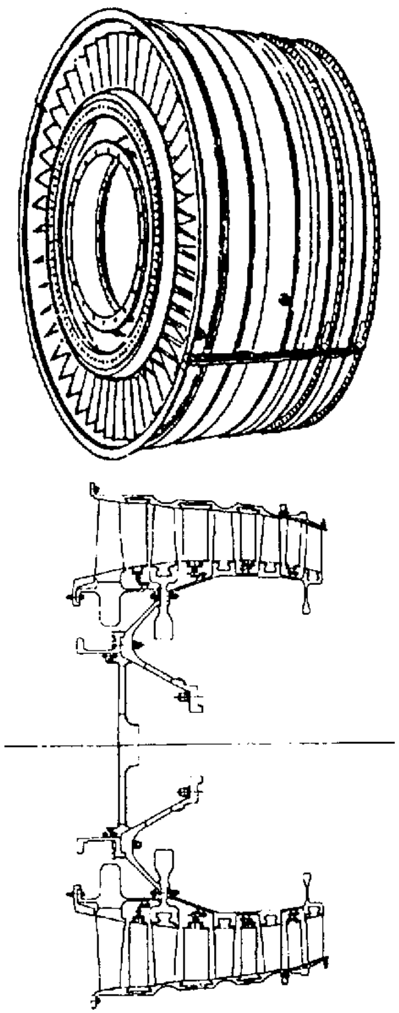
- ***Anodized Aluminum***

Forward Drive Adapter



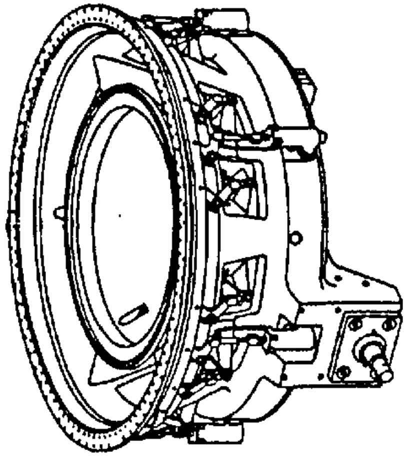
Same for PC, PD, PF, PG & PH

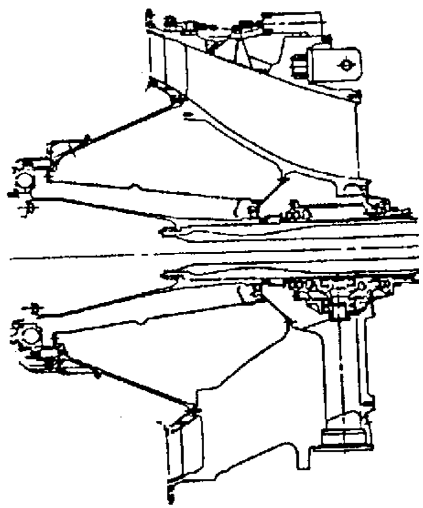
Low Pressure Compressor



- Common with LM5000
  - Derived from CF6-50
  - modified for cold end coupling adapter
- 5-stage axial flow compressor
  - 2.4:1 pressure ratio
  - Driven by LP turbine
- Horizontal split stator case provides access to blades and vanes
- Boroscope provisions for internal flowpath inspection
- Individual compressor blade replacement
- ***Improved efficiency stage 0-3 vanes***

Front Frame



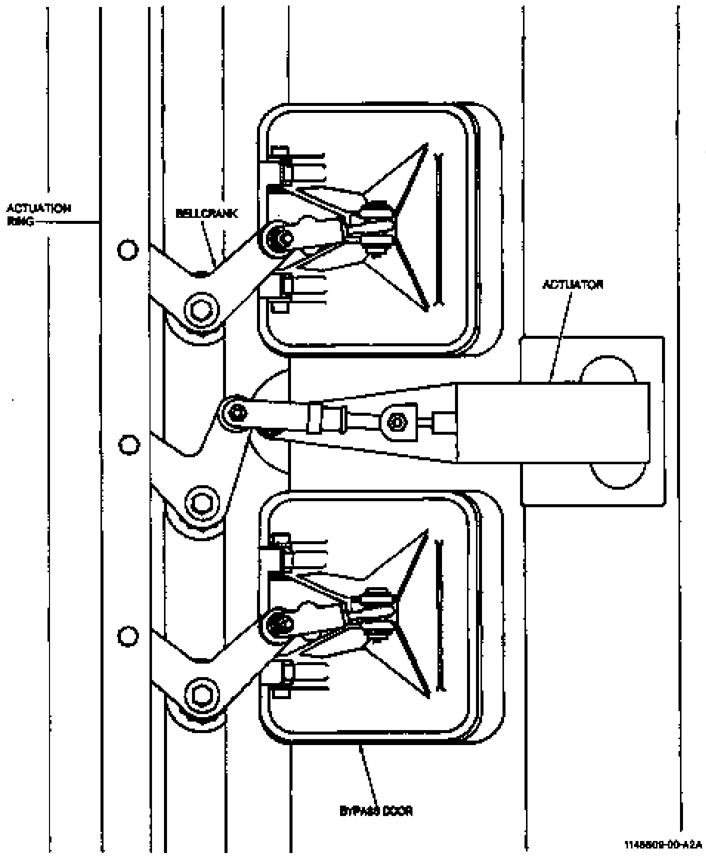


- Twelve strut frame contains A-sump, bearings, inlet gearbox, and front engine mounts
- Structural support between LPC casing and HPC casing
- 12 variable bypass valves (doors)
  - Helps optimize LPC/HPC airflow matching during acceleration, deceleration and part load operation
  - Hydraulically actuated
  - Doors fully closed at approximately 75% load
- One piece 17-4PH steel casting eliminates welded and brazed joints

imagination at work

Variable Bleed Valves

Same for PC, PD, PF, PG & PH

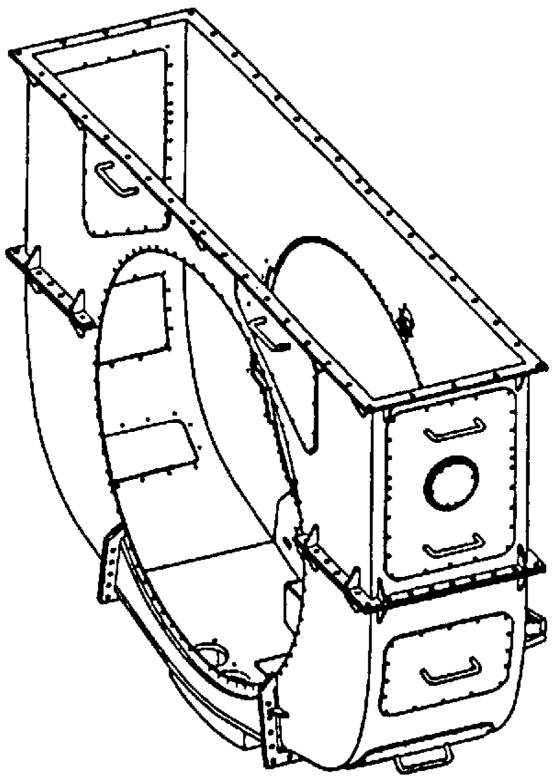


Variable Bleed Valves

- Control LPC Op Line
- PC (&PG) Increased in size by +60% over PA
- Additional Hydraulic Supply

Bypass Air Collector

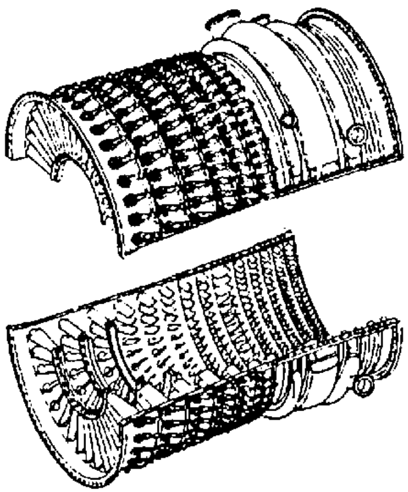
Same for PC, PD, PF, PG & PH

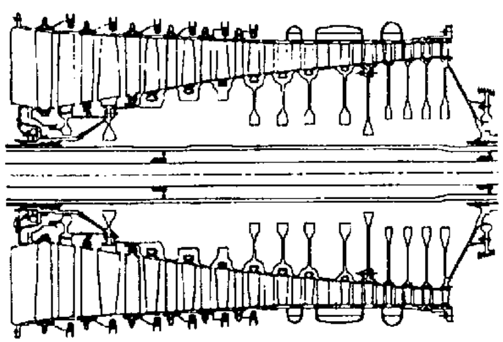


- Directs compressor bypass air off-engine
- Upper flange 81” X 18”
- AMS 5062 carbon steel
- Supports accessory gearbox

imagination at work

High Pressure Compressor Stator



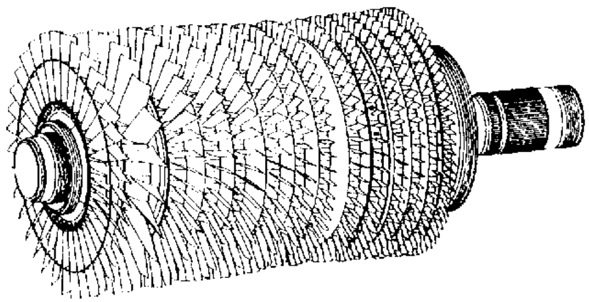


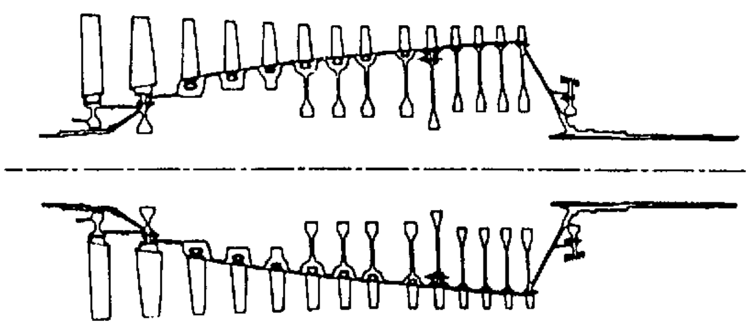
- Common with CF6-80C2
- First six stages have variable stator vanes
  - Enhanced part load efficiency
  - Hydraulically actuated
- Horizontally split casing
  - Field removable
  - Individually replaceable vanes
- "Trenched" inner case improves tip clearances and sustains efficiency
- Inter-stage bleed air provisions for cooling and balancing at stages 7, 8 and 11
- Customer bleed air provisions at stages 8 & 14 (CDP)
- Boroscope inspection ports at each stage
- High strength M152 steel casing
- **Stg 11 vanes common to –80E**

imagination at work

High Pressure Compressor Rotor

New material 3-9 spool, new material S14 disk, bleed changes

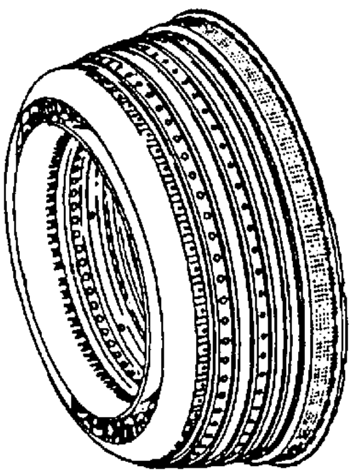


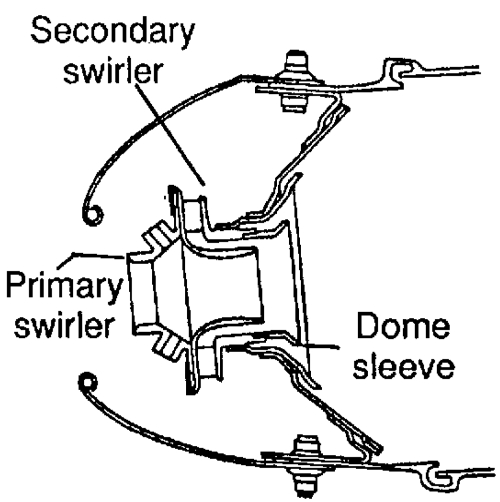


- Derived from CF6-80C2
- 14-stage axial flow compressor ✓
- Simple six piece construction
  - Disk/rotor design of fewer parts and greater rigidity
  - Inertial welded disk/shaft for increased strength and optimum materials selection ✓
- Corrosion resistant materials eliminates need for coatings ✓
- Individually replaceable blades
  - Stages 1 & 2 axial dovetails
  - Stages 3 to 14 radial dovetails ✓
- Mid span damper on 1st stage provides vibration damping ✓

imagination at work

LM6000 PC Combustor





- Common with CF6-80C2

- Annular machined ring construction
  - Minimal cooling air required
  - Uniform temperature profile to HPT
  - Better resistance to thermal stress
  - Short residence time decreases NOx
  - Ideal for frequent starts

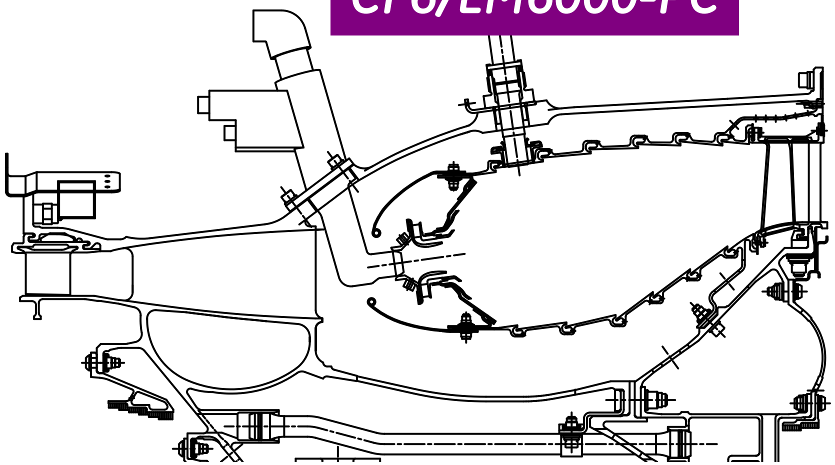
- 30 fuel nozzle ports
  - Counter-rotating swirler design provides improved fuel/air mixing and NOx suppressant flow pattern

- Corrosion resistant Hastelloy X inner liner, HS-188 outer liner and dome

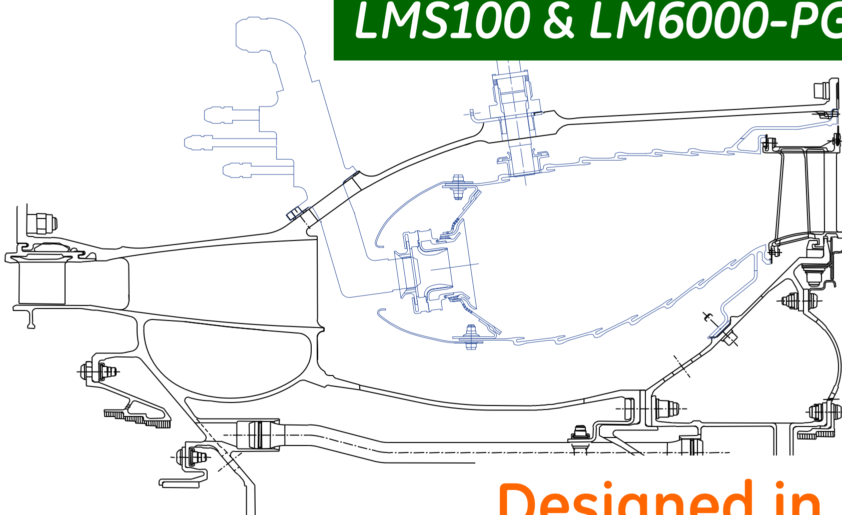
- Thermal barrier coating on internal surfaces

Standard Annular Combustor (SAC) based on proven design

CF6/LM6000-PC



LMS100 & LM6000-PG



LMS100-PA/-PG Combustor

- Starting design base: CF6-80C/LM6000
- Same CRF Volume & Diffuser
- Areas Redesigned for Operability & Performance:
  - Fuel Nozzle
  - Swirler
  - Liners
- Areas Redesigned for Reliability Improvements:
  - A. Fuel Nozzle
  - B. Swirler / Ferrule
  - C. Splashplate
  - D. Domeplate Cooling pattern
  - E. Venturi

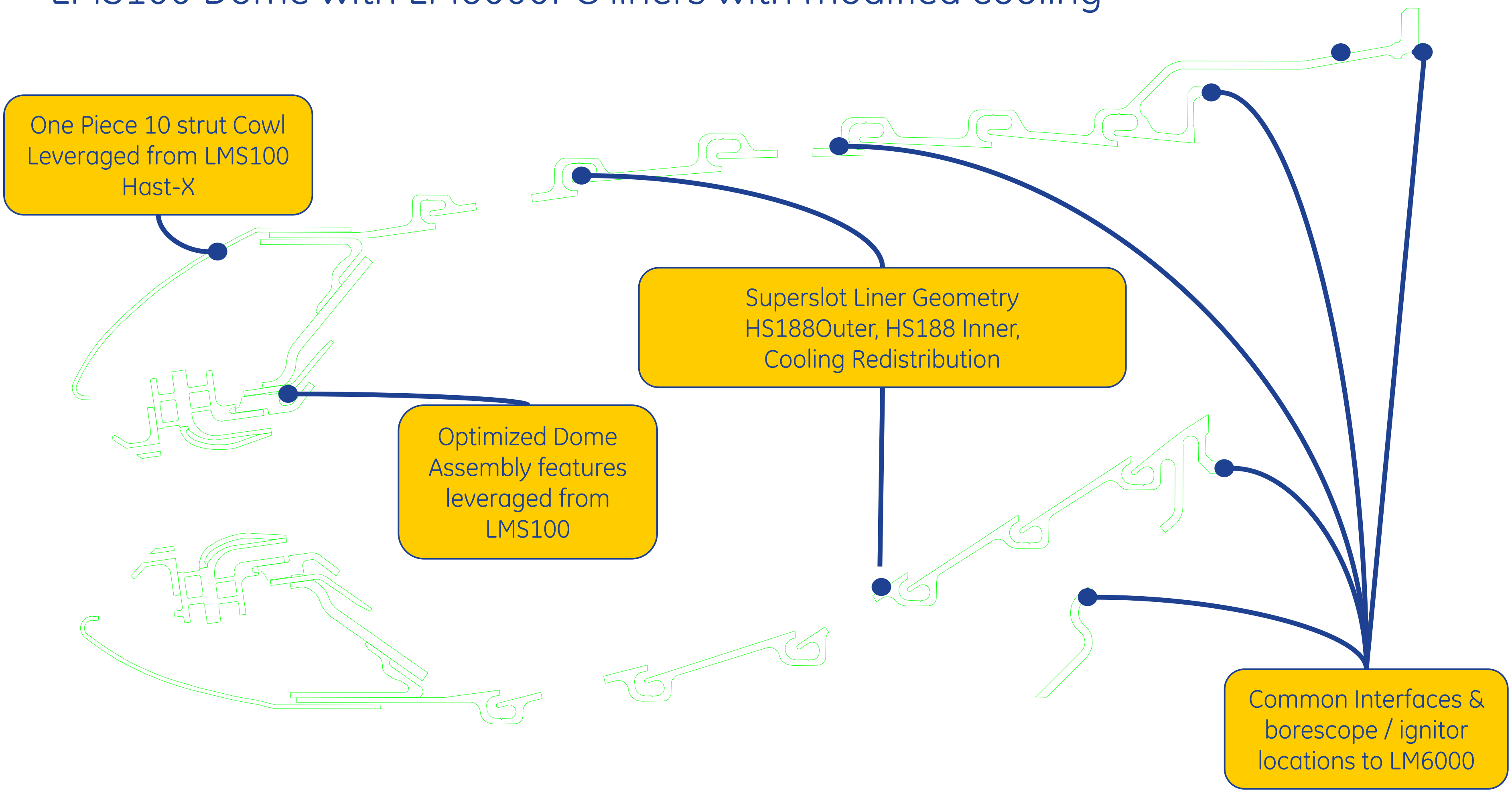
Designed in Lessons Learned

– Rig and Core Test to Validate Design

imagination at work

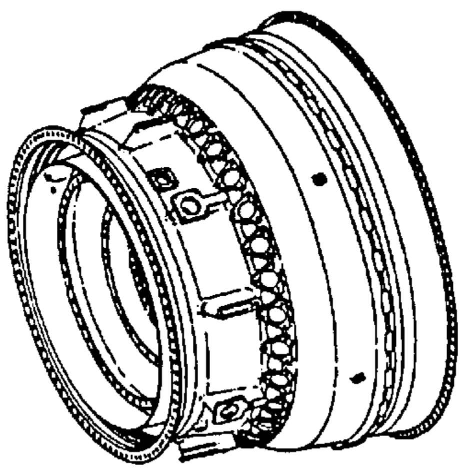
LM6000PG Combustor

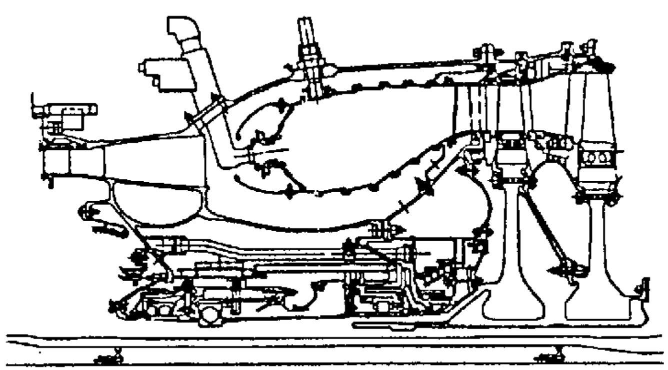
LMS100 Dome with LM6000PC liners with modified cooling



imagination at work

SAC Compressor Rear Frame





•Similar to CF6-80C2 ▪ -PC
Similar to CF6-80E & LMS100 ▪ -PG

• 10 radial struts

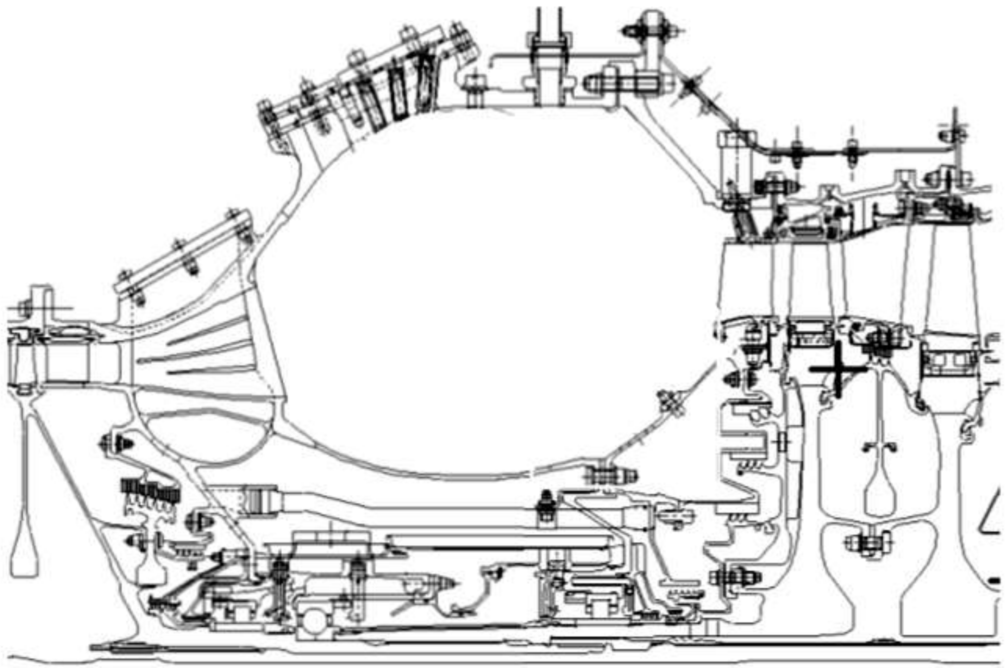
• Structural support between HPC stator and LPT stator cases

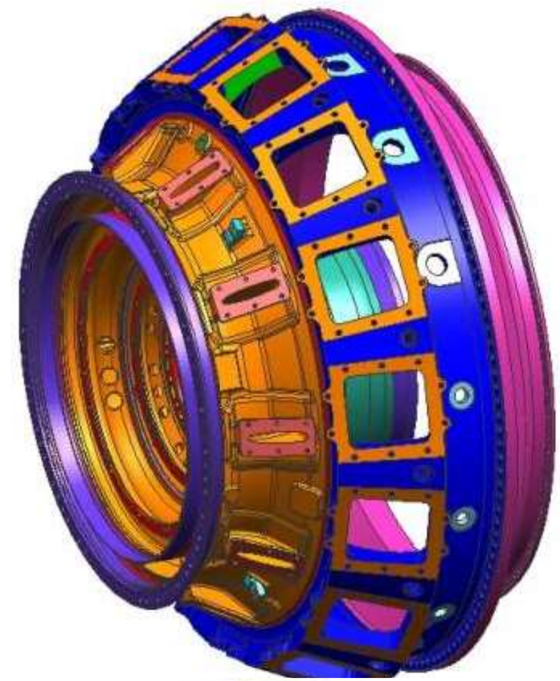
• Contains annular combustor, HP rotor bearings, B-C sump, HP turbine and openings for fuel nozzles

• 8 boroscope ports for inspection of combustor, fuel nozzles, turbine blades and nozzles

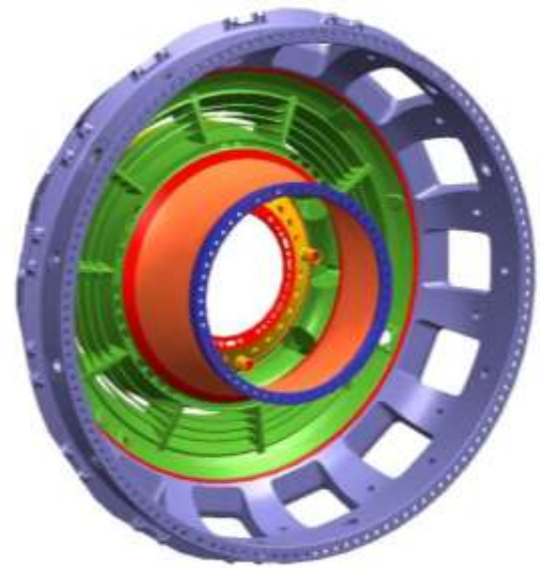
• Inco 718 fabrication

LM6000PH CRF Hardware Details

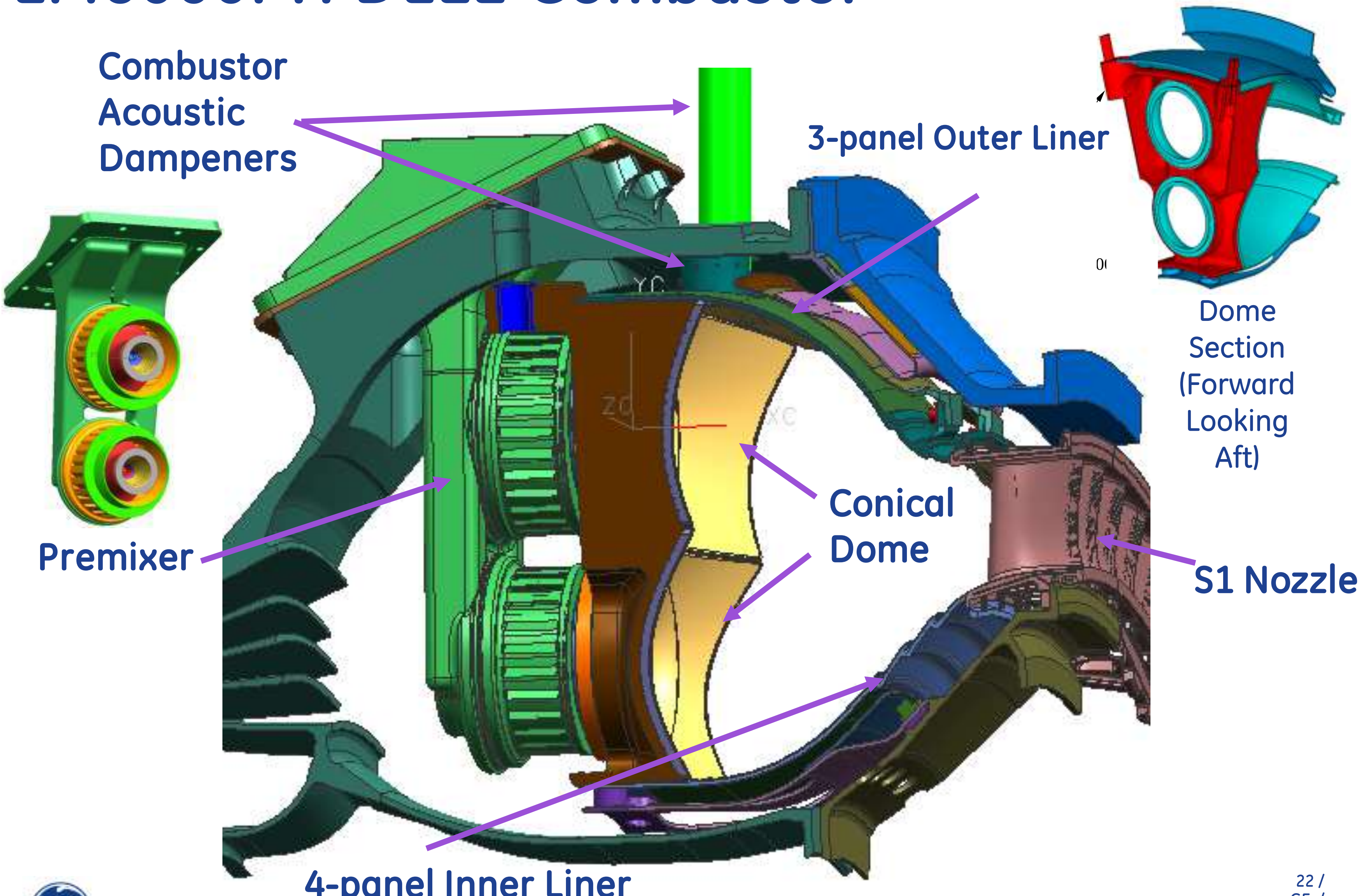




- PH CRF is leveraged from LMS100 DLE and PD

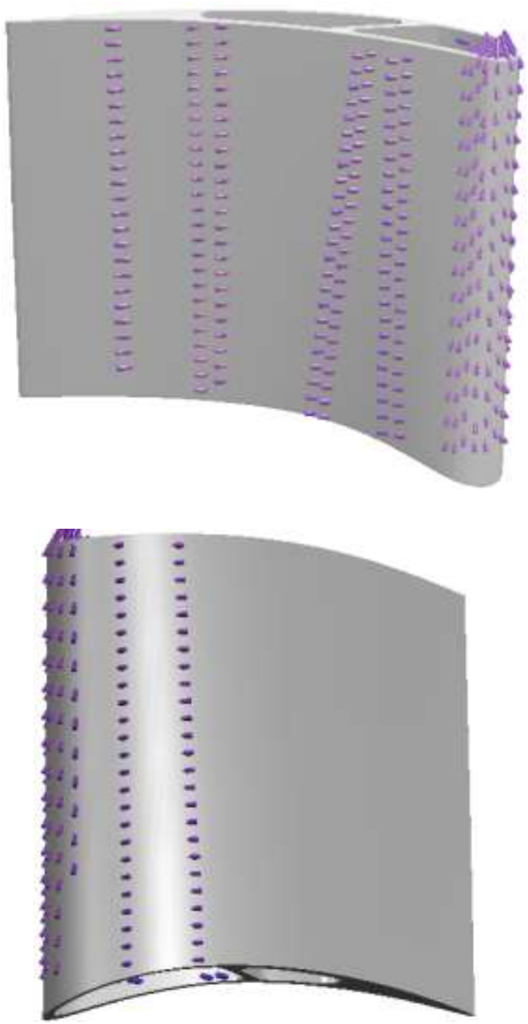


LM6000PH DLE2 Combustor

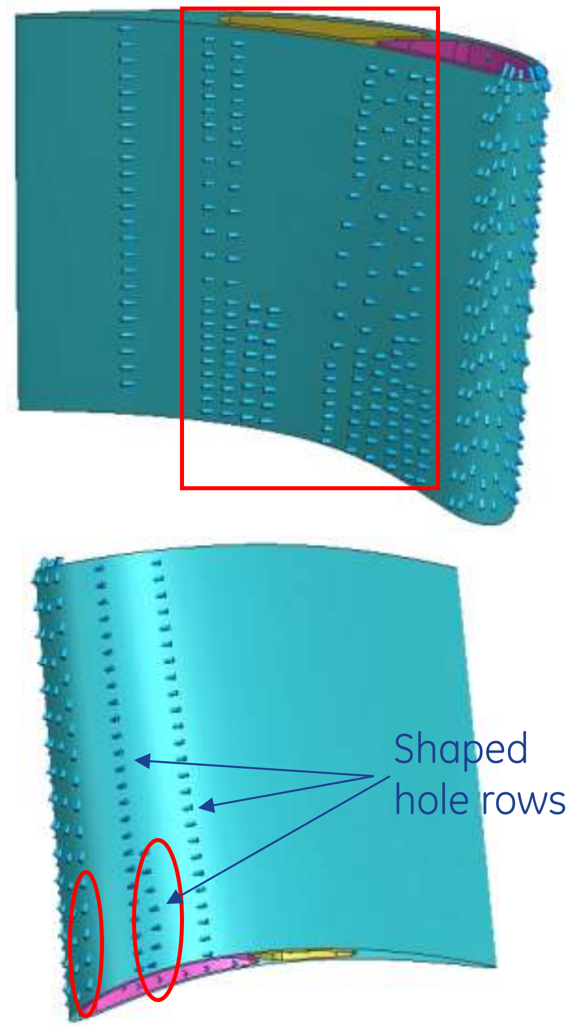


LM6000PH HPT S1 Nozzle Changes

PG



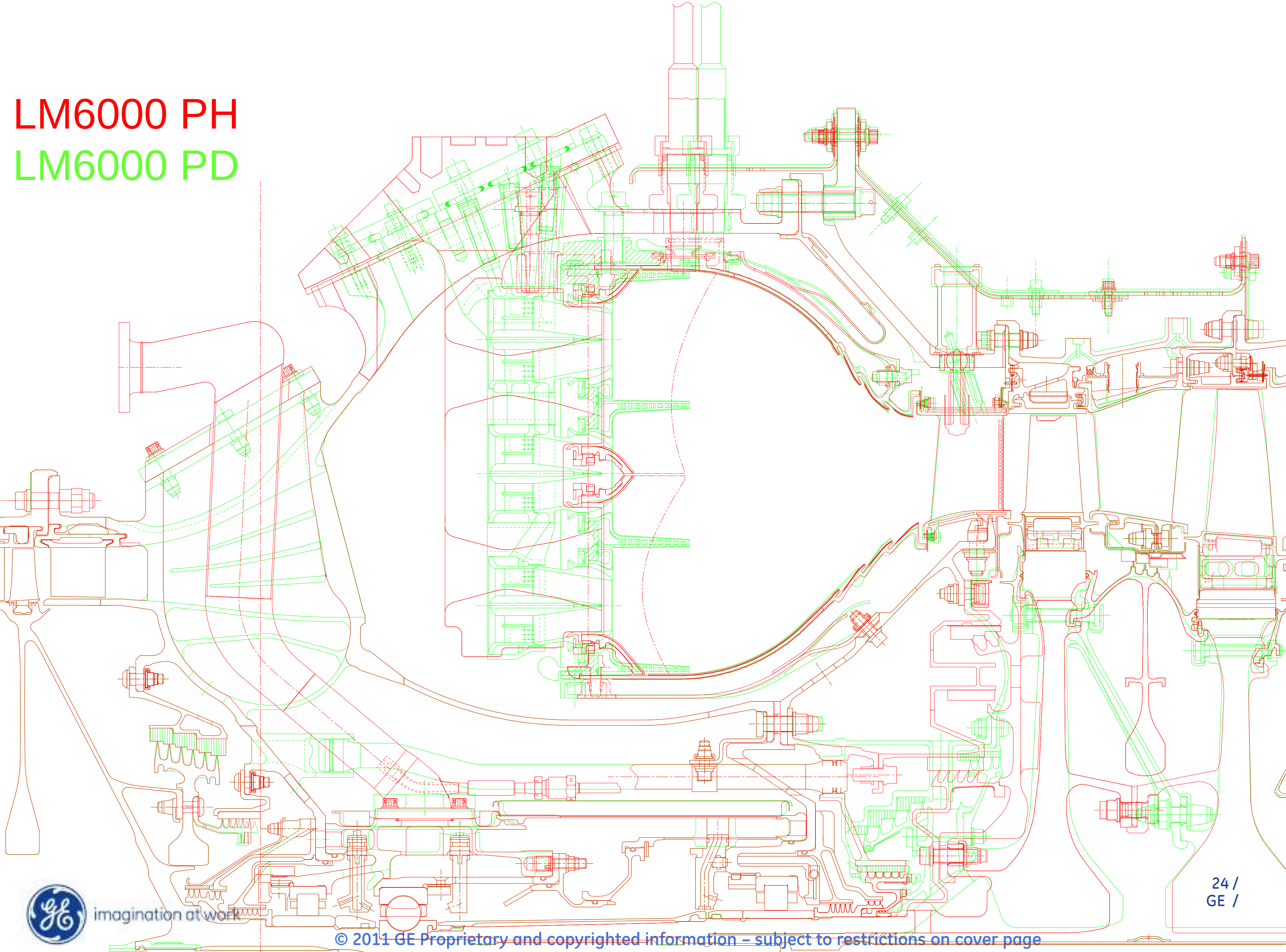
PH

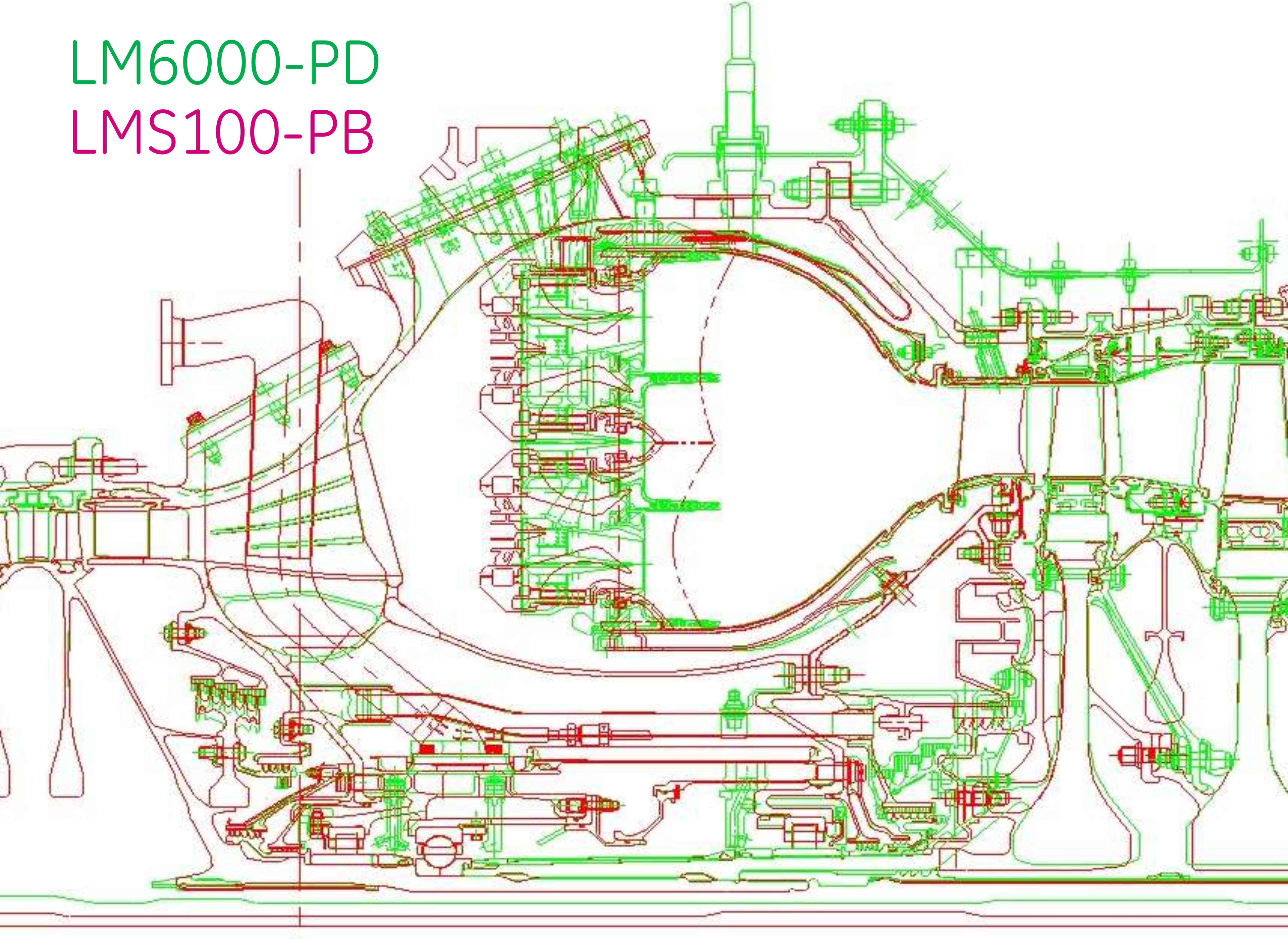


imagination at work

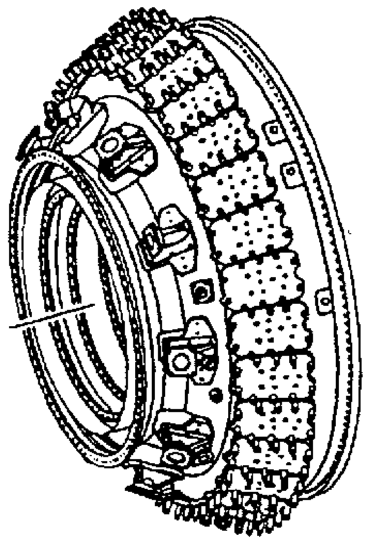
LM6000 PH

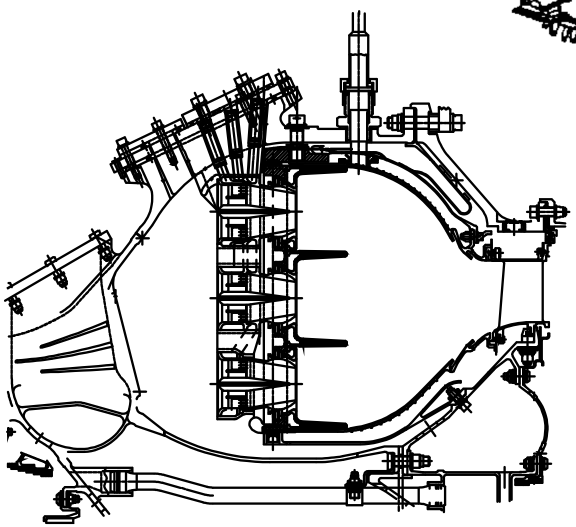
LM6000 PD




LM6000-PD
LMS100-PB

-PD/-PF Compressor Rear Frame

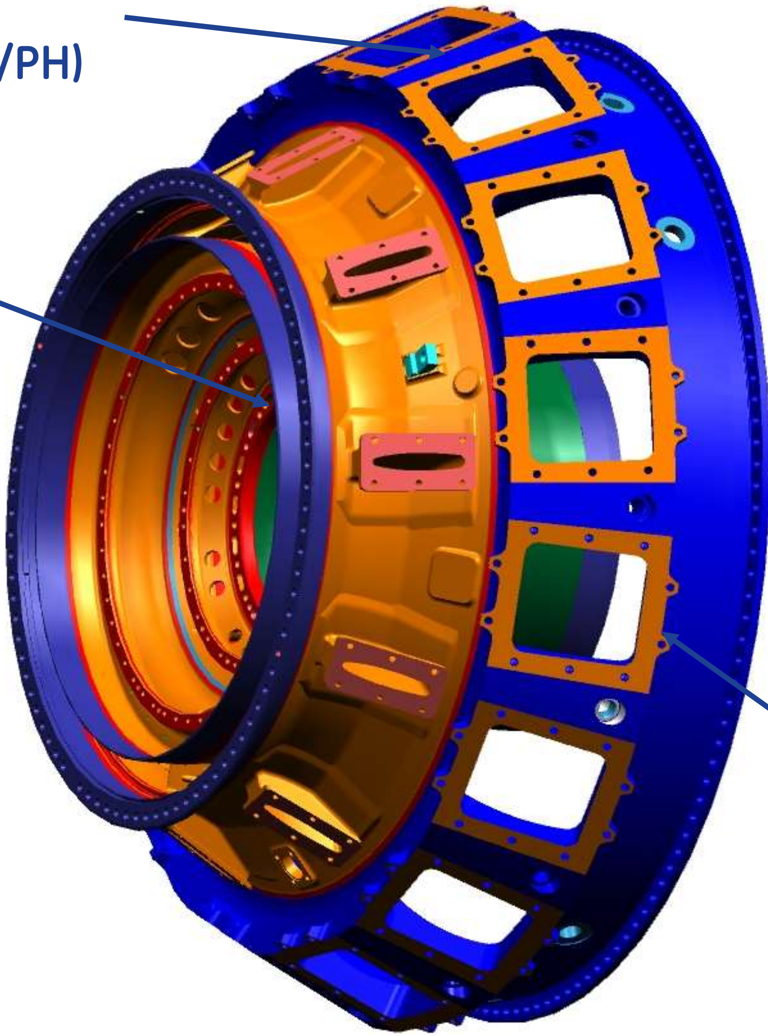




- Developed for DLE combustion system
- 10 radial struts with integral split diffuser
- Structural support between HPC stator and LPT stator cases
- Contains annular DLE combustor, HP rotor bearings, B-C sump, HP turbine and openings for premixers
- 8 boroscope ports for inspection of DLE combustor, premixers, turbine blades and nozzles
- Inco 718 fabrication

imagination at work

-PH Compressor Rear Frame



Diffuser Casting
(common with LM6PD/PH)

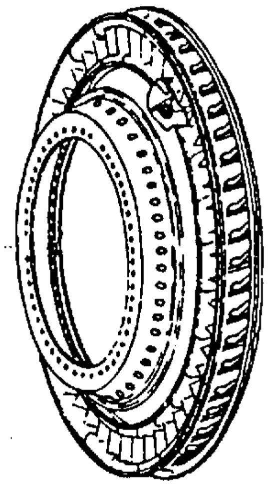
Aft Hub Flange
Forging
(Mat'l common to
LM6PD)

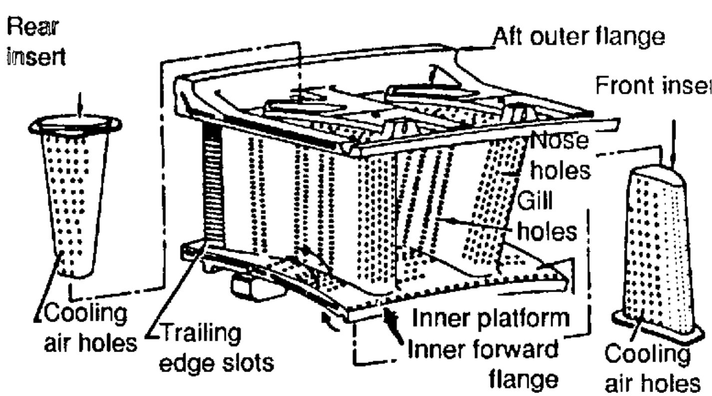
Aft Inner Skirt
and Aft Flange
Forging
(Mat'l common
to LM6PD)

Fuel Nozzle Ring
(common with LMS100)

imagination at work

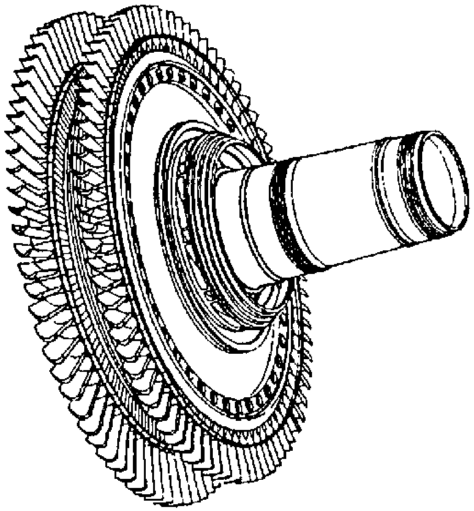
Stage 1 HP Turbine Nozzle Assembly



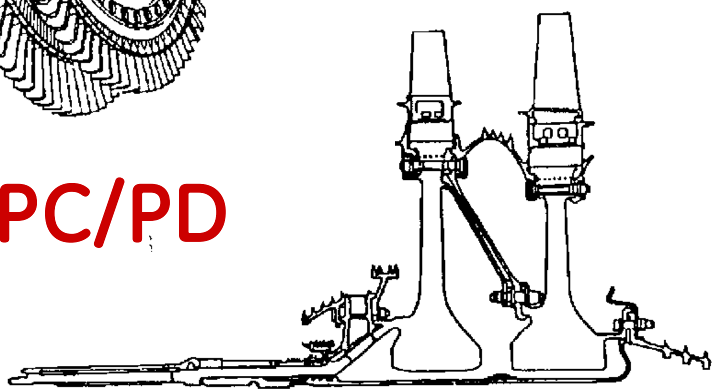


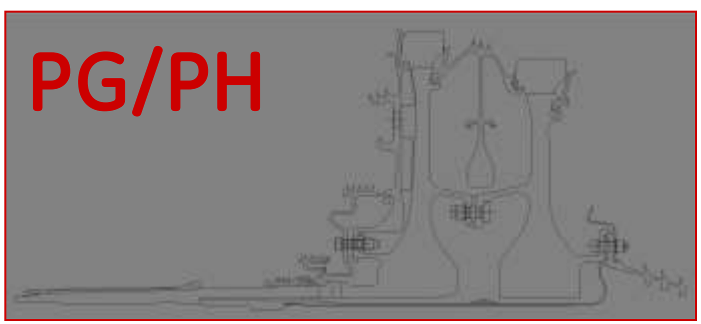
- Derived from CF6-80E
- Directs hot gas stream to stage 1 rotor blades ✓
- 23 two-vane segments, one with borescope inspection port ✓
- Internally cooled with HP compressor discharge air ✓
  - Tubular inserts promote improved cooling air distribution
- Directionally Solidified DSR 142 nickel alloy ✓
- Aluminide Coated ✓
- Thermal Barrier Coating

High Pressure Turbine Rotor



PC/PD



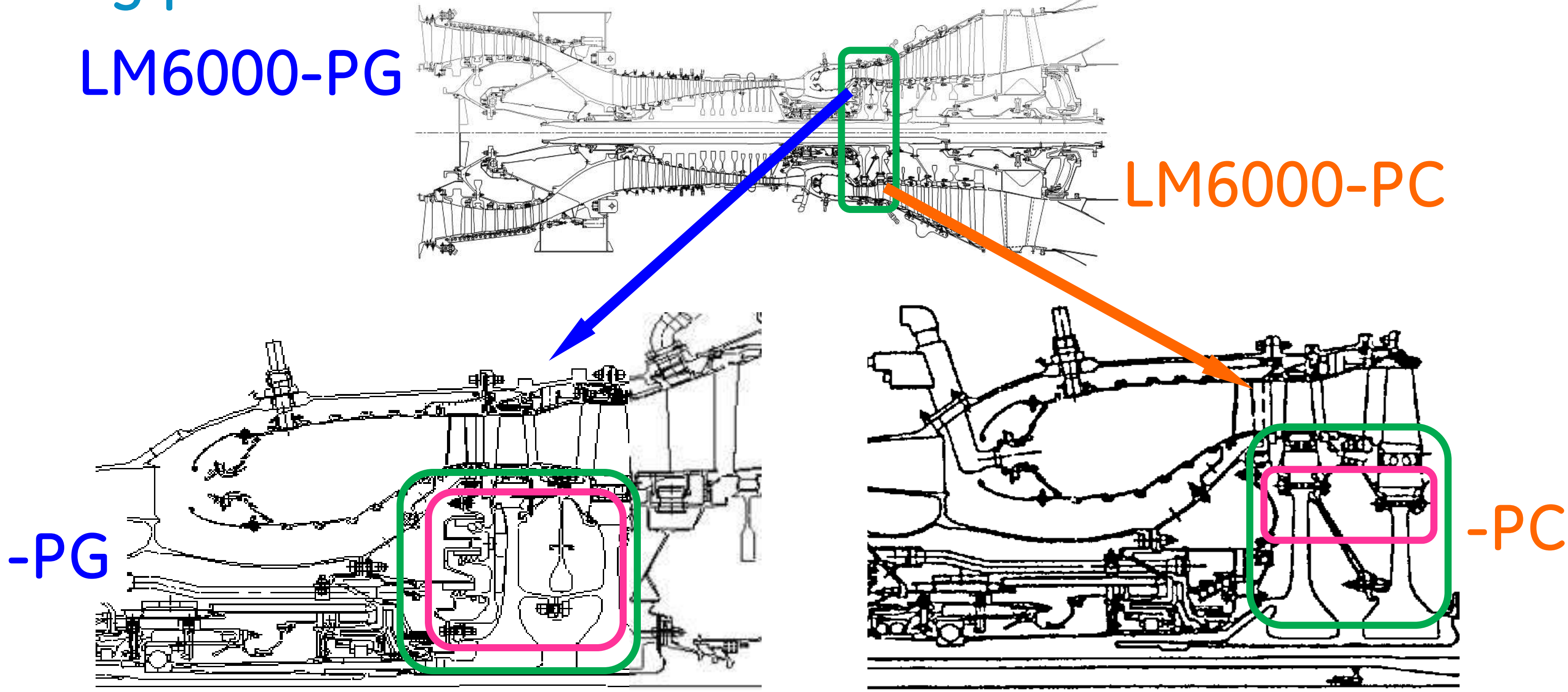


- Two-stage cantilevered rotor drives high pressure compressor
- Disks and blades air cooled; improved cooling circuits for greater efficiency
- Inertia-welded disk/shaft for greater strength, fewer parts
- Coated blades for increased resistance to erosion and corrosion
  - Platinum aluminide & TBC external coating
  - Aluminide internal coating
- “Boltless” rotor design
- Advanced disk/seal materials

imagination at work

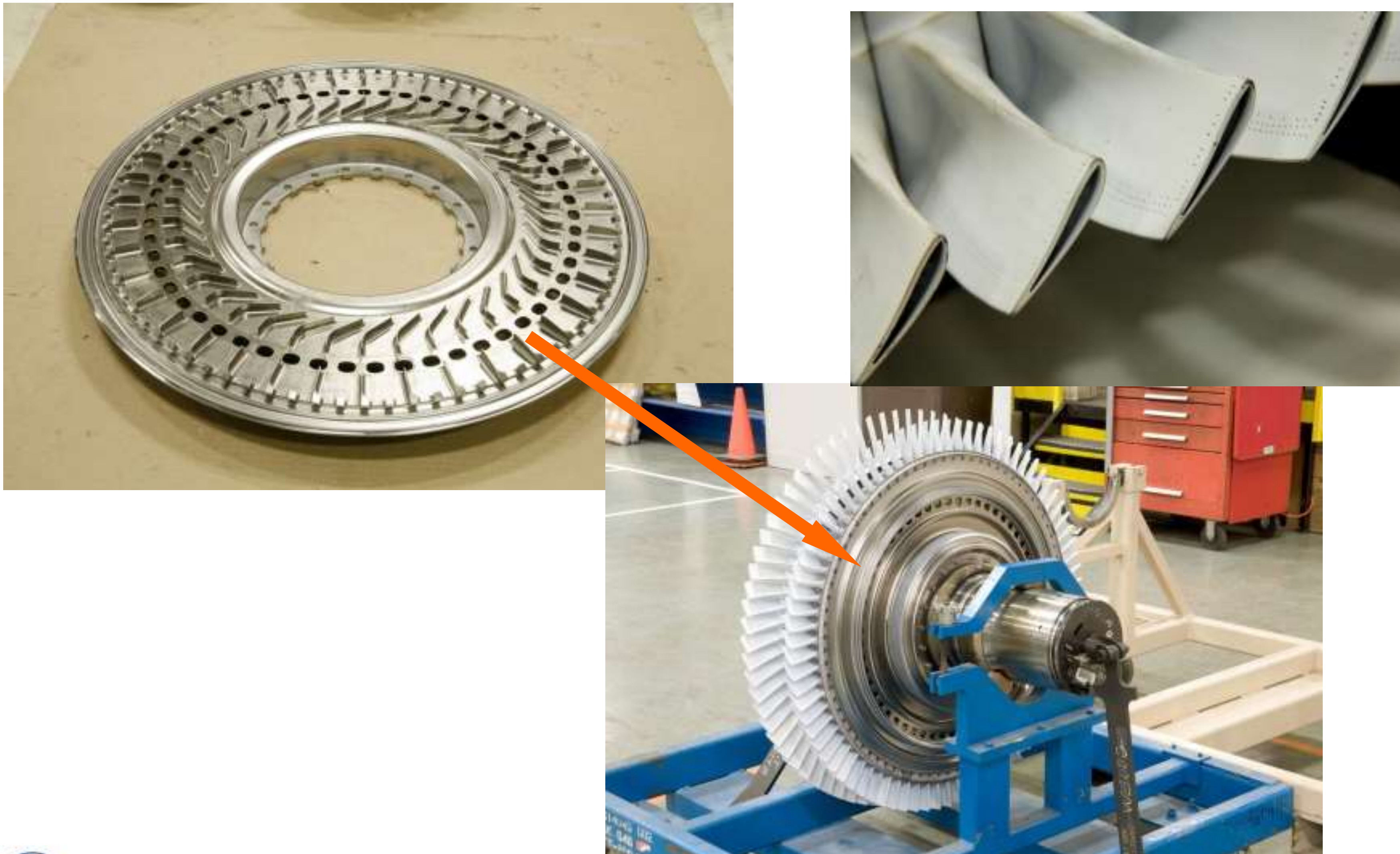
60% Better cyclic life

Using proven –80E1 HPT rotor construction

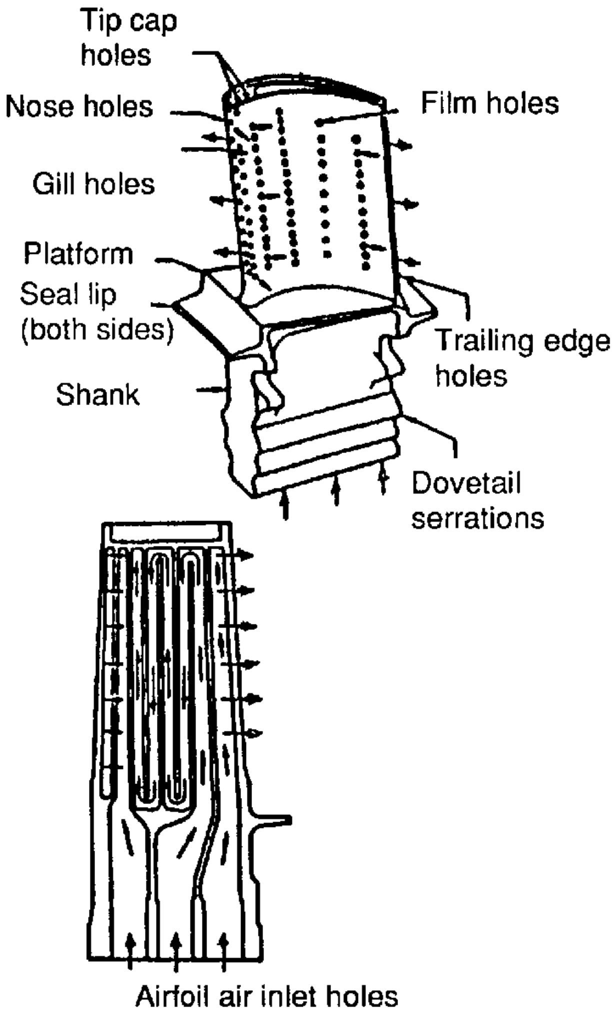


- ✓ New bolt pattern for lower stress
- ✓ Higher temperature alloys
- ✓ Improved cooling patterns

Improved cooling for the HPT Rotor



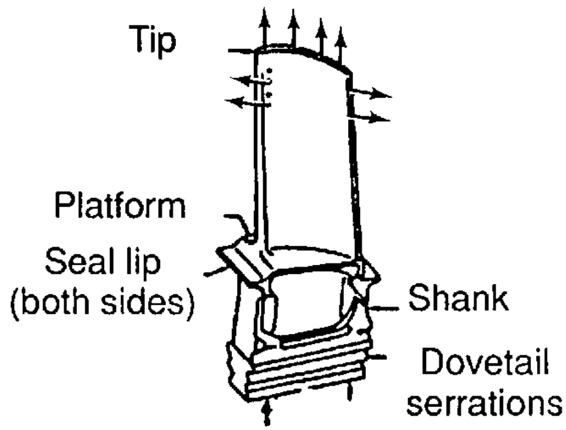
HP Turbine Stage 1 Blade

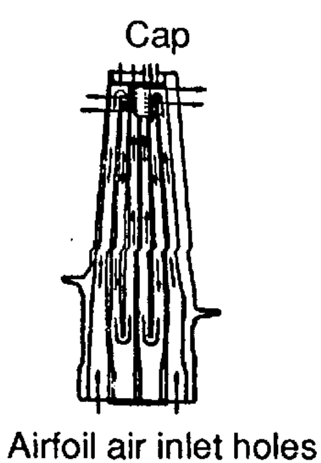


- PG blade similar to PC
- Eighty air cooled blades
  - PG/PH model has single crystal N5 blades
- Laser drilled cooling holes ✓
- Internal turbulence promoters for better cooling ✓
- Corrosion resistance coatings ✓
  - Platinum aluminide & TBC on external surfaces
  - Aluminide on internal surfaces

imagination at work

HPT Stage 2 Blade

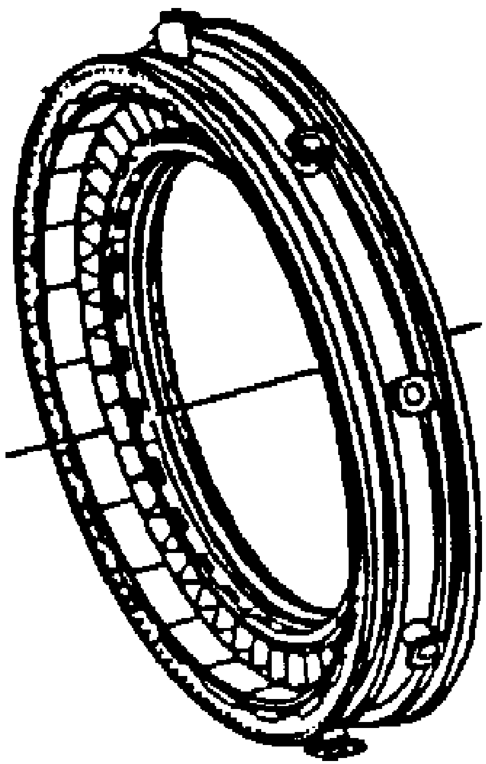


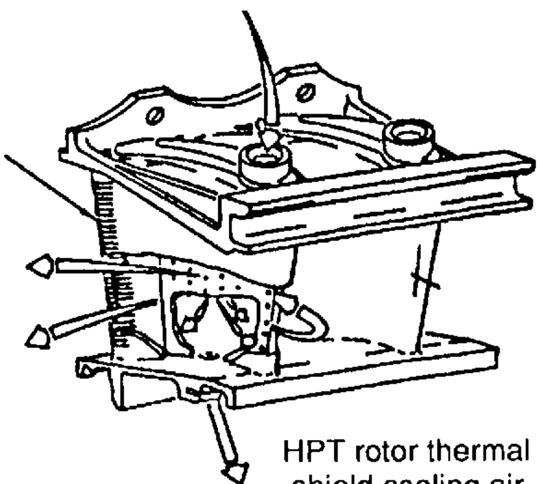


- PG blade similar to PD
- Seventy-four blades ✓
- Laser drilled cooling holes ✓
- Internal convection air cooling ✓
- Corrosion resistance coatings ✓
  - Platinum aluminide on external surfaces
  - Aluminide on internal surfaces
  - TBC coating added to PG/PH

imagination at work

Stage 2 Nozzle Assembly



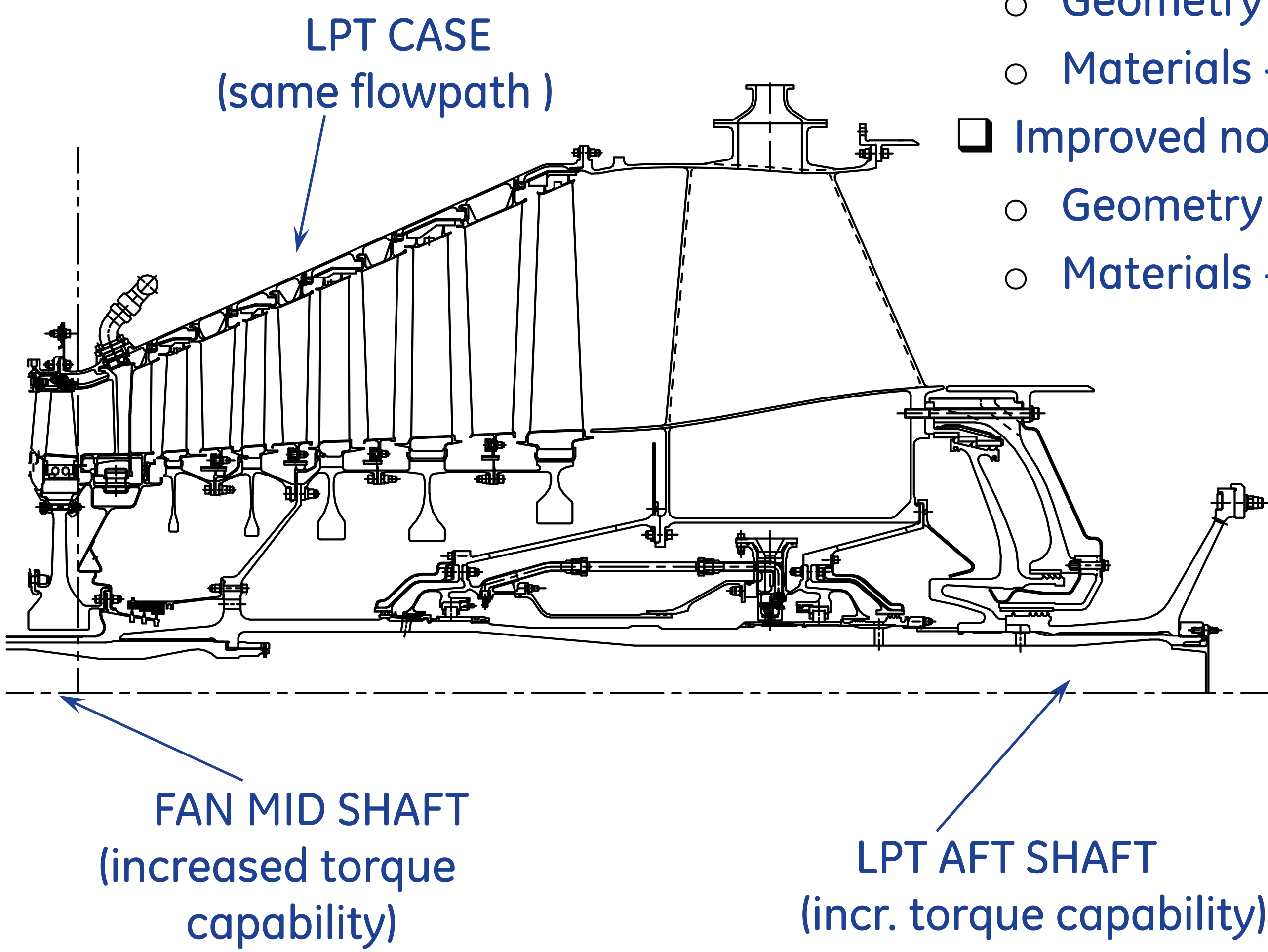


- 24 two-vane segments, one with borescope inspection port
  - Individually repairable or replaceable segments
- Cast Rene N5 plus Aluminide coating and TBC
- Internally cooled with Ilth stage air

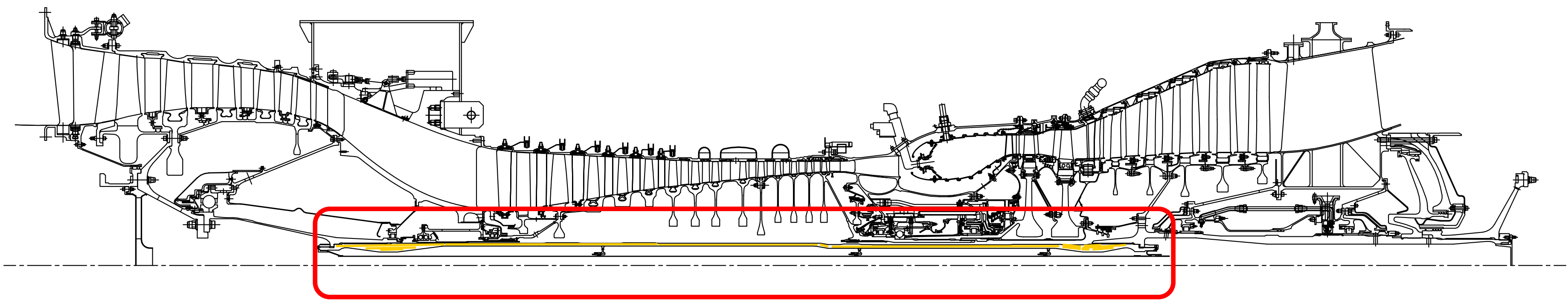
Low Pressure Turbine

From –PC/PD to –PG/PH

- ❑ Improved blade airfoil
  - o Geometry - Stage 1 and 5
  - o Materials - Stage 1 and 2
- ❑ Improved nozzle airfoil
  - o Geometry - Stage 1 and 2
  - o Materials - Stage 2



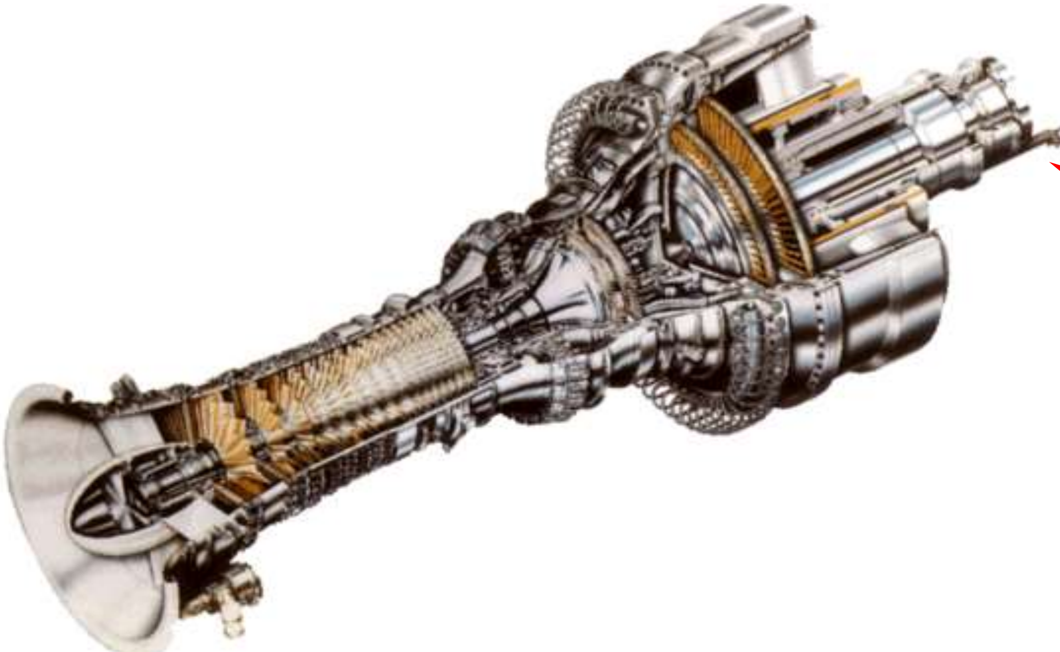
LP “Fan” Midshaft



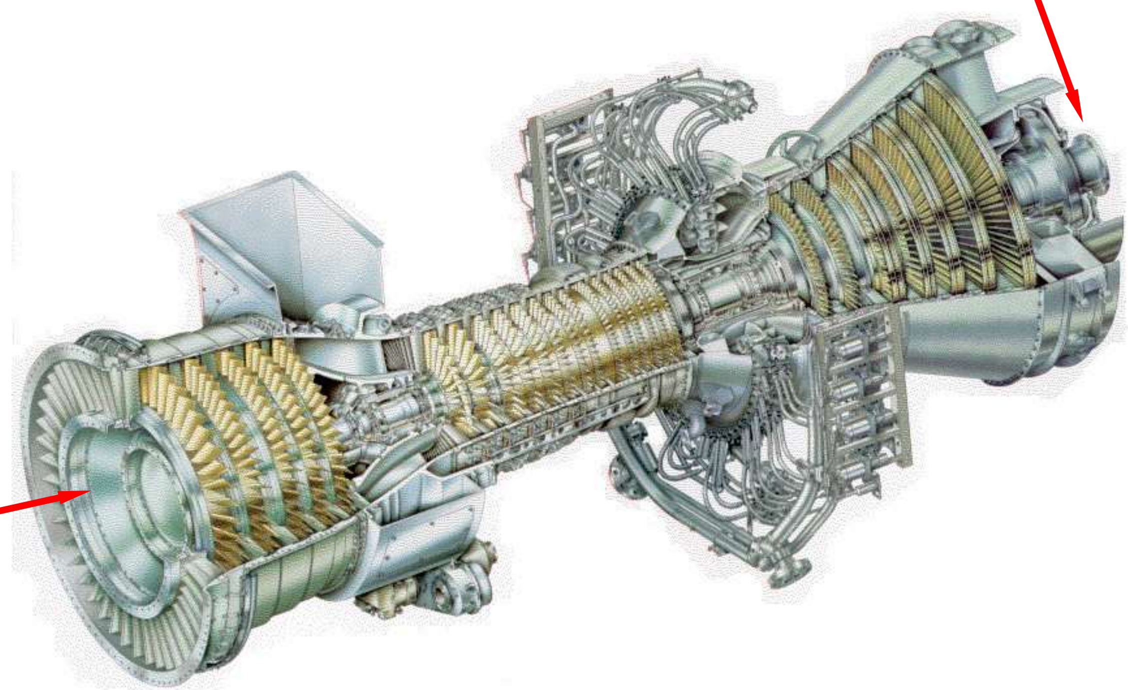
LP Midshaft

- Approx 6” diameter X 0.3” wall
- Marage Steel
- More robust spline

Drive Flexibility



Hot-end Drive

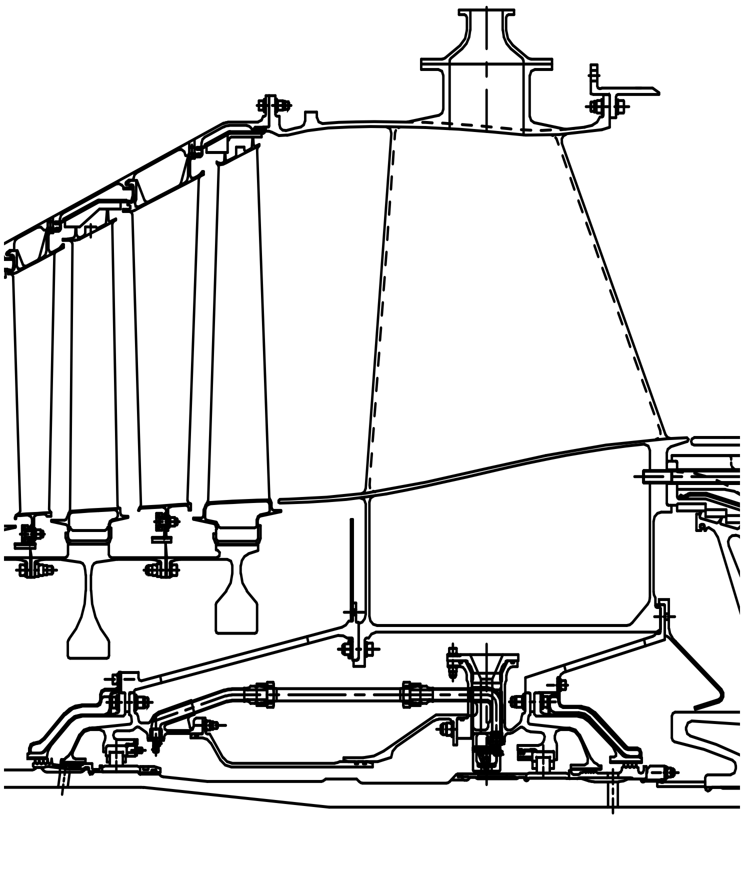


Cold-end Drive

imagination at work

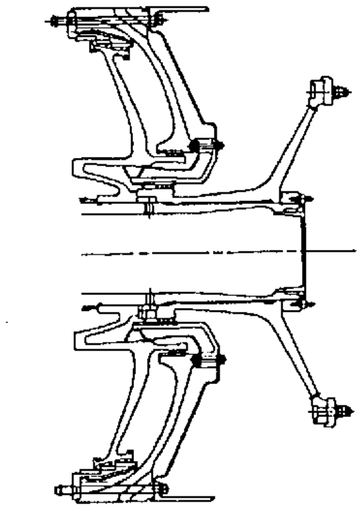
Turbine Rear Frame

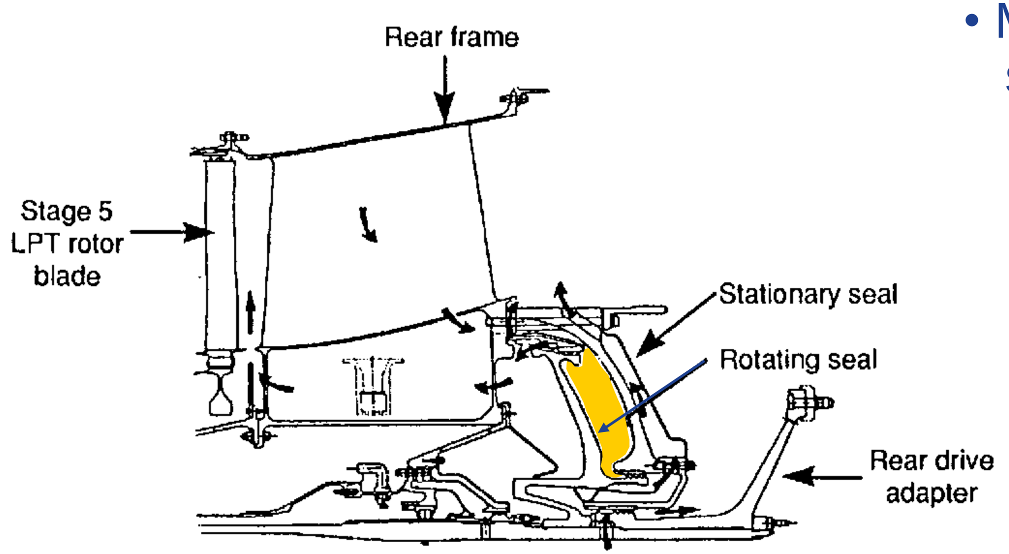
Similar for PC and PG



- Interface to exhaust duct
- Diffusing flow path
- High Exit Velocities from LPT
- ***14-strut*** frame provides guide vane function for improved exhaust flow characteristics
- Contains D-E sump
- One piece Inco 718 casting, no welded or brazed joints
- Location of rear engine mounts
- Damped No.7R Bearing for PG/PH

LP Rotor Thrust Balance Piston



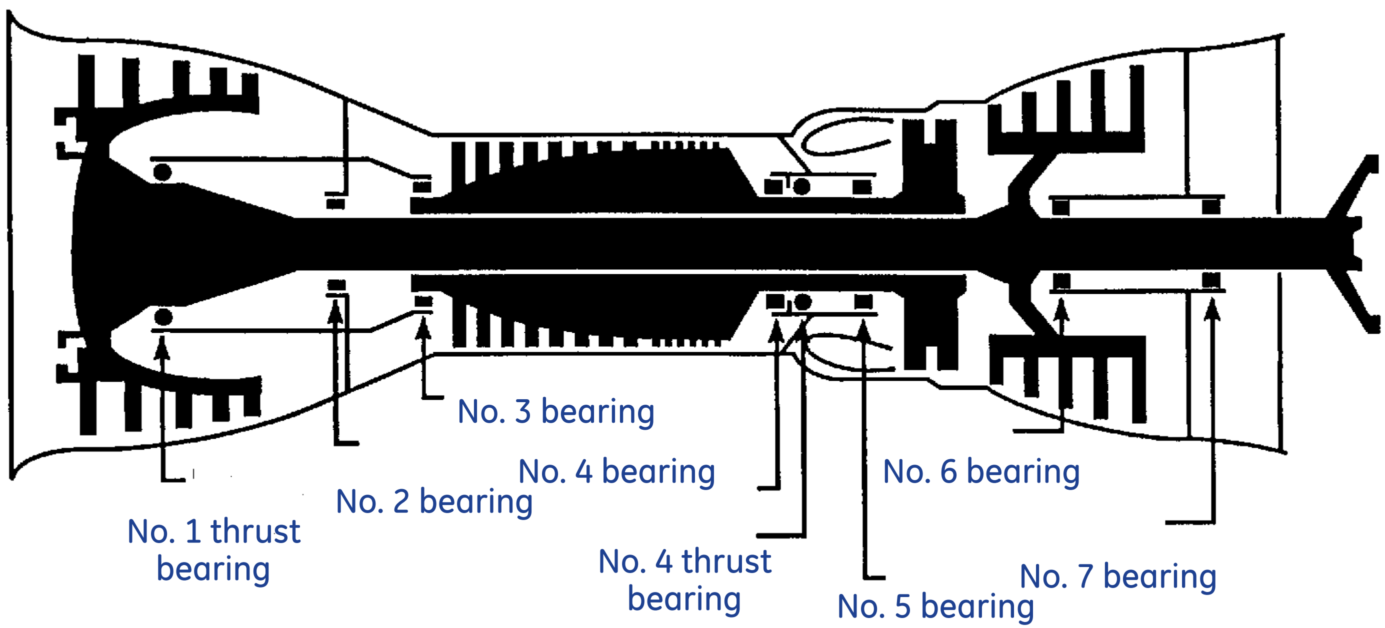


Similar for PC and PG

- Maintains proper load on LP rotor thrust bearing
- Air supply from HPC stage 11 bleed
- Inco 718 rotating seal
- M152 steel stationary seal

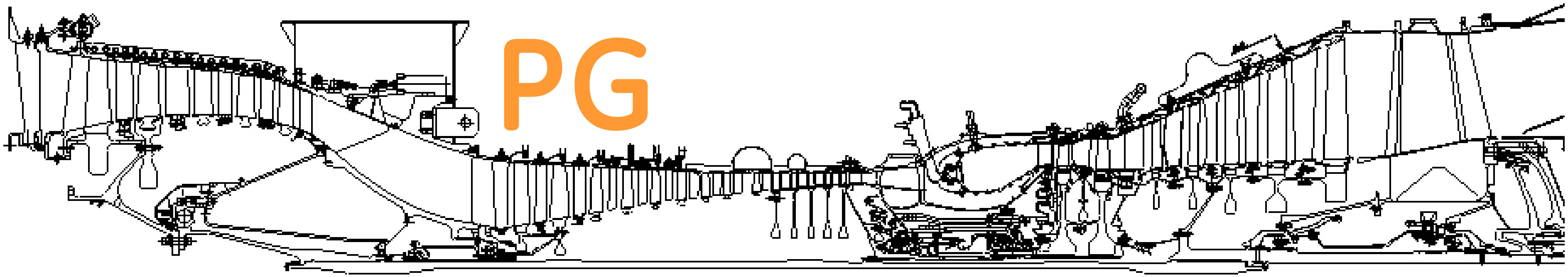
imagination at work

Rotor and Bearing Arrangements

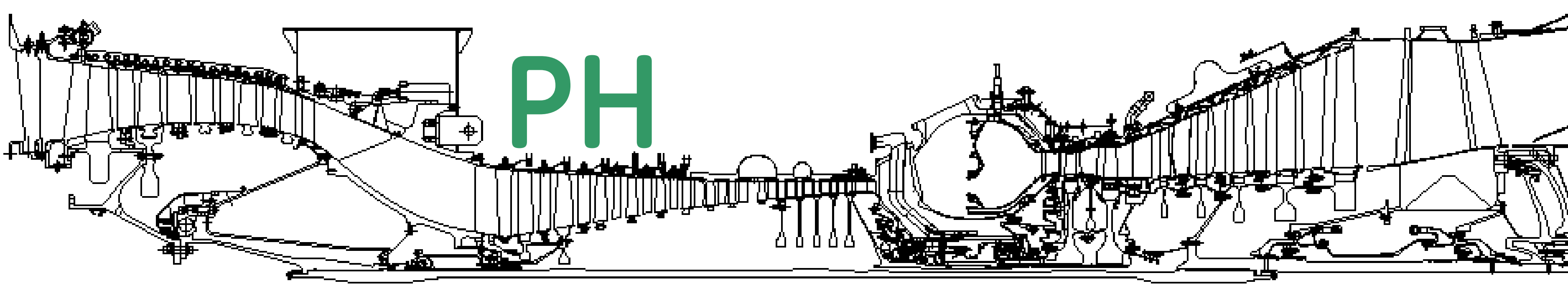


- Bearings number 1 and 4 absorb rotor thrust loads
- Smaller lube oil system required due to antifriction bearings
- Coast down with no damage from loss of oil supply
- Added damper to No. 7 bearing for –PG/PH

LM6000PG/PH By the Numbers



PG		PH
20,088	Engine level parts to Assemble	21,425
2,477	Part numbers	2,808
165	New part numbers for PG/PH	251
93%	Commonality with previous version	91%



imagination at work

Component Materials

Low pressure compressor	-PC/PD/PF	-PG/PH
- Cold end drive flange	***B5F5 + Ser Metel W***	***PQ B5F5 + Ser Metel W***
- Stator casings - front	Aluminum and anodize	Aluminum and anodize
- Stator casings - rear	321SS +17-4 PH	321SS +17-4 PH
- Vanes - inlet guide	***Anodized Aluminum***	***Anodized Aluminum***
- Vanes - stages 1, 2	***Ti-6Al-4V***	***Ti-6Al-4V***
- Vanes - stages 3, 4	Ti-6Al-4V	Ti-6Al-4V
- Blades - stages O, 1	A286	A286
- Blades - stages 2, 3, 4	Ti-6Al-4V	Ti-6Al-4V
- Rotor disks - stages O, 1	B5F5 + Ser Metel 725	***PQ*** B5F5 + Ser Metel 725
- Rotor spool - stages 2, 3, 4	Ti-6Al-4V	Ti-6Al-4V
- Forward shaft	B5F5 + Ser Metel W	***PQ*** B5F5 + Ser Metel W
- Mid shaft	Marage 250 + Ser Metel	Marage 250 + Ser Metel
- Front frame	17-4 PH	17-4 PH
- Air collector	AMS5062 + polyurethane	AMS5062 + polyurethane
High pressure compressor		
- Stator casing	M152	M152
- Blades - stages 1-5	Ti-6Al-4V	Ti-6Al-4V
- Blades - stages 6-9	A286	A286
- Blades - stages 10-14	Inco 718	Inco 718
- Vanes - stages 0-14	A286	A286
- Rotor disks - stage 1, 2	Ti-6Al-4V	Ti-6Al-4V
- Rotor disks - stage 10	Inco 718	Inco 718
- Rotor spools - stages 3-9	Ti-6Al-2Sn-4Zr-2Mo	**Inco 718**
- Rotor spools - stages 11-14	Inco 718	Inco 718, **Stg 14 disk R104**
- Compressor discharge seal	Rene'41	**R104**
- Rear frame	Inco 718	Inco 718

Component Materials (Cont.)

	-PC/PD/PF	-PG/PH
SAC Combustor		
- Outer liner	HS188 + TBC	HS188 + TBC
- Inner liner	Hastelloy X + TBC	HS188 + TBC
DLE Combustor		
- Liners	Mar M509 + TBC	Mar M509 + TBC
- Heat Shields	N5 + TBC	N**4** + TBC
- Premixers	Inco 625	Inco 625
High pressure turbine		
- Nozzles - stage 1	DSRene' 142 + Aluminide	N5 + Aluminide + TBC
- Nozzles - stage 2	Rene'80 + Aluminide	R142 + Aluminide + TBC
- PC Blades - stage 1	DS Rene' 142 + platinum/aluminide + TBC	
- PD/-PG/-PH Blades - stage 1	N5 + platinum/aluminide + TBC	N5 + platinum/aluminide + TBC
- Blades - stage 2	Rene'80 + platinum/aluminide	DS Rene'142 + platinum/aluminide
- Disks/shafts - stages 1, 2	Inco 718	R104
- Spacer	Inco 718	R104
- Thermal shield	Rene'41	R104
Low pressure turbine		
- Stator casings	Inco 718 + Waspaloy	Waspaloy
- Blades and nozzles - stages 1	B&N=Rene'80 + Codep B	B=N4, N=Rene'80 + Aluminide
- Blades and nozzles - stage 2	B&N= Rene'77 + Codep B	B=Rene'125, N=Rene'80 + Aluminide
- Blades and nozzles - stage 3	B&N= Rene'77 + Codep B	B=Rene'77, N=Rene'77
- Blades and nozzles - stage 4, 5	B&N= Rene'77 + Codep B	B&N= Rene'77 + Codep B
- Disks - stages 1 to 5	Inco 718	Inco 718
- Rear frame	Inco 718	Inco 718
- Hot end drive flange	4340 (AMS 6414)	4340 (AMS 6414)

N5

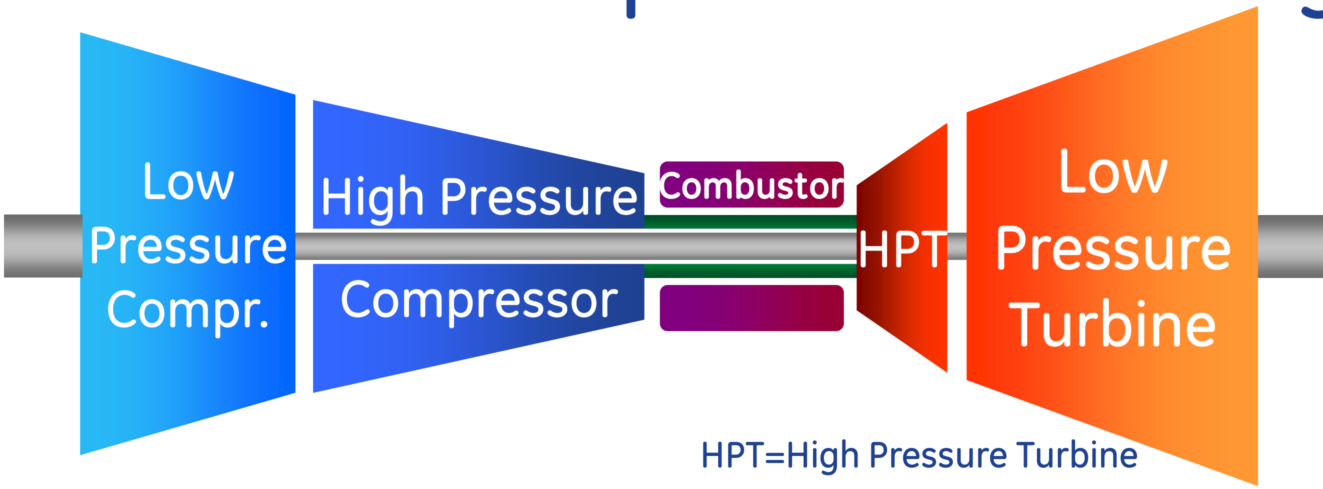
R125

Comparison to Commercial Engine Technical Data

Sources: # http://geae.com/engines/commercial/index.html * http://www.airweb.faa.gov/					Turbine exhaust gas temperature indicated (T49)	
Model	Max. thrust Sea Level (lbf) ISO Power (shp)		Max. Low pressure rotor speed (N1 - rpm)	Max. High pressure rotor speed (N2 - rpm)	Takeoff (5 min.)	Maximum continuous
CF6-50	51,000 - 54,000		4,102	10,761	1733°F (945°C)	1670°F (910°C)
LM6000 -PC/-PD	70,300		3,780	10,700		1600°F (871°C)
CF6-80C2	52,500 - 63,500		3,854	11055	1760°F (960°C)	1697°F (925°C)
LM6000 -PG/-PH	81,100		3,930	10,711		1702°F (928°C)
CF6-80E	67,500 - 72,000		3,835	11,105	1787°F (975°C)	1724°F (940°C)
GE90-115B	115,300		2,602	11,292	1994°F (1090°C)	1922°F (1050°C)

imagination at work

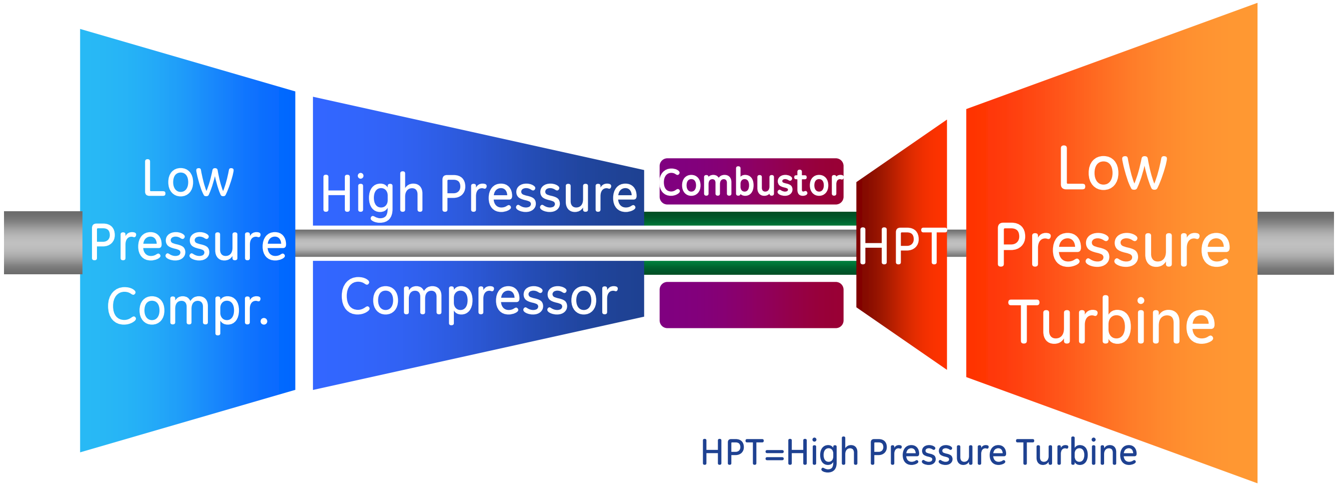
Evolution based on proven technologies



	Max LP Rtr Speed	Max HP Rtr Speed	T3 ºF	T48 ºF	Press. Ratio **Max**; ISO	# of units	Cum. Exp hrs
CF6-50 (Max Take-off)	4102	10761		1733	31.1	1700	>125 MM
LM6000-PC/PD	3780	10700	1010	1600	**32.3**; 30.7	>1000	>21 MM
CF6-80C2 (Max T/O)	3854	11055		1760	31.9	>3600	>170 MM
LM6000-PG/PH	3930	10711	1080	1702	**34.8**; 32.6		
CF6-80E1 (Max T/O)	3835	11105		1787	32.6	>450	9 MM
LMS100	3600	9650	728	1600	38.9	23	>56 k
GE90 (Max T/O)	2602	11292		1859	42	>1100	>22 MM

imagination at work

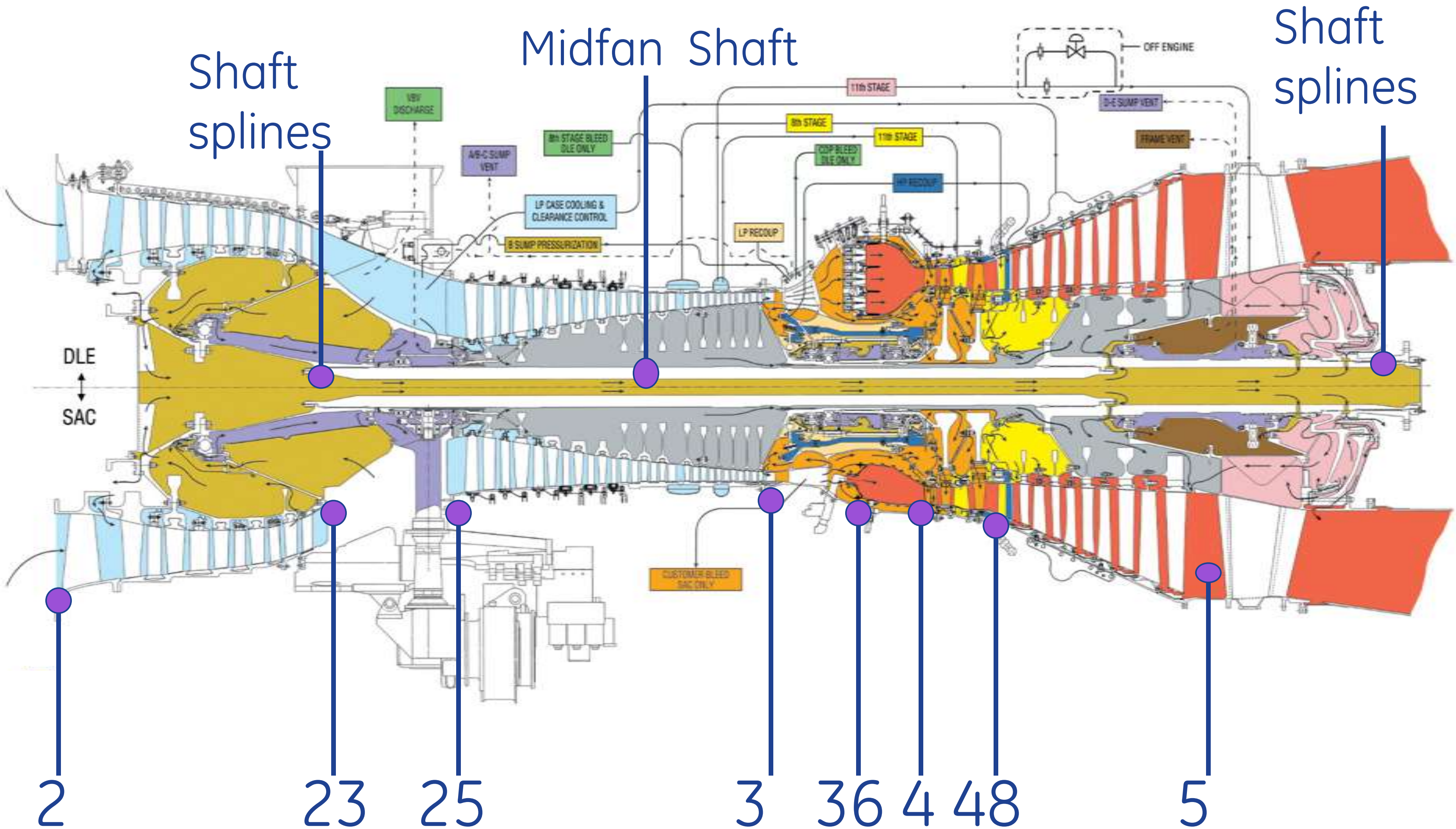
Evolution based on proven technologies



	Max LP Rtr Speed	Max HP Rtr Speed	Max T3 ºF ºC	Max T48 ºF ºC	T8 ºF ºC	Press. Ratio Max; ISO	Fuel flow MBtu/hr GJ/hr	Airflow lb/s kg/s
LM6000-PC/PD& PF	3780	10700	1010/999 543/537	1600/1592 871/867	809/855 432/455	32.3; 30.7	374/352 394/371	283/275 128/125
LM6000-PG/PH	3930	10711	1080 582	1702 928	861/885 461/474	34.8; 32.6	463/406 488/428	318/303 144/138
LMS100-PA	3780	9650	690	1600	760 405	38.9	809 854	480 218

imagination at work

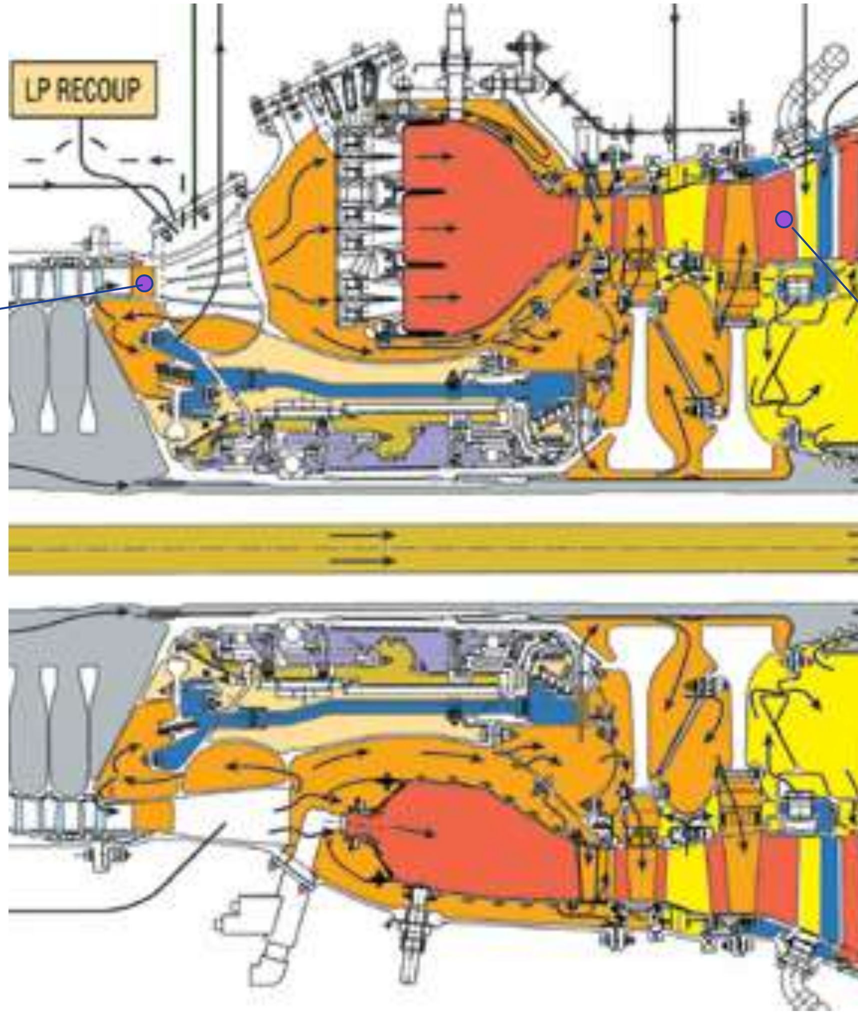
LM6000 PD over PC Airflow



imagination at work

LM6000 PC over PD – Combustion & HPT Sections

Compressor Discharge Temperature (T3)



LP Turbine Inlet Temperature (T48)

imagination at work

Station definitions

- 0 → 1 Ambient to inlet
- 1 → 2 Inlet to compression
- 2 → 3 Compression
- 3 → 4 Combustion
- 4 → 5 Expansion
- 5 → 6 Mixing to afterburning
- 6 → 7 Afterburning to nozzle
- 7 → 8 Nozzle convergence
- 8 → 9 Nozzle divergence to exhaust
- 9 → 0 Exhaust to ambient