Propulsion Strategy for the 21st Century – A Vision into the Future

By

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Abstract

GE Aircraft Engines' (GEAE) commercial and military customers are striving toward products with low cost of ownership. This drives GEAE to high performance, light weight, low noise and low emission designs. GEAE has adopted a two-part strategy. First is to develop single-stage high-pressure turbine (HPT) machines for the narrow body/regional market, and second, develop a two-stage HPT, high pressure ratio architecture for the wide body, long range operations. To this end GE has defined a two-step technology process: the TECH56, and the Ultra Efficient Engine Technology (UEET) programs. Work on fan, compressor, and turbine aerodynamics is in process.

Great strides to improve the environmental impact of aircraft engines are being taken. GEAE is working on NOx reduction with the TAPS combustor and on noise control with chevron nozzles.

The paper also describes GEAE's Global Engineering and University initiatives.

Introduction

GE Aircraft Engines' strategy is driven by customer satisfaction. We must develop some key enabling technologies now to facilitate our product development vision for the next twenty years and our engine architecture for the years to come. We also need to develop and refine our tools to improve our Thruput and Quality. All of this can only come about by focusing the best talent available around the world.

Discussion

Let us first talk about Customer Satisfaction. Our commercial and military customers have been telling us that we needed to drive towards a low cost of ownership and we have been listening. To accomplish this, we have been driving our engine designs in the direction of simplicity, reliability, improved performance, low noise, and low emissions. These quality parameters have set our product strategy for the future.

Figure 1 shows this strategy. For the Regional and Narrow-Body market, we will maintain the CFM56/ CF34-10 architecture in our future engines. This architecture incorporates a 2-shaft machine with a single-stage high-pressure turbine at a moderate pressure ratio. The product definition in that thrust-class is driven, primarily, by simplicity, low parts count, and high reliability dictated by the high cycle operations.

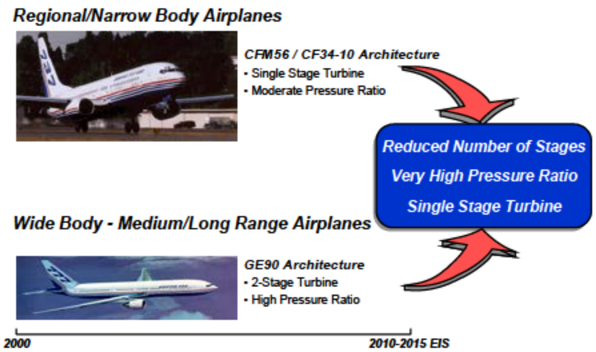


Figure 1. GEAE Product Strategy.

Now, for the Wide-Body medium and long range markets we believe that the GE90-architecture, a 2-shaft machine with a 2-stage high pressure turbine, and high overall pressure ratio, yields the ultimate fuel burn performance and range so important for these applications.

Our strategy is to eventually merge these two architectures and go to a single-stage high-pressure turbine configuration with very high pressure ratios and a reduced number of stages. We believe that the technologies necessary to make this happen should be available by the year 2010, and the resulting products become available in the following decade.

What are we doing to get there? Well we start from two solid bases: our CFM56 and GE90 families. The first step is expressed by our Project TECH56 program where we are developing new technologies for every engine component (shown in Figure 2).

Our goals for the program, depending on the application, are:

- a 4 to 7% fuel burn improvement relative to the current CFM56
- a 15 to 20% lower maintenance cost
- a reduction of NOx to 50% below the ICAO level, and
- a cum 20dB noise level margin relative to FAR36 Stage III

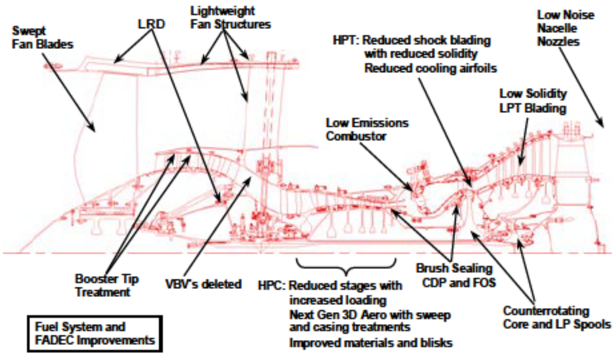


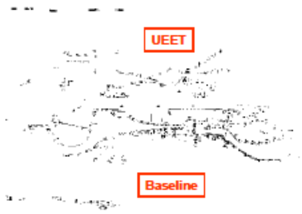
Figure 2. Project TECH56.

We have been working on Project TECH56 for close to 3 years and the program is right on track. I will describe some of the results a little later.

Our second step is to move to what we call the Ultra Efficient Engine or UEET that we are developing with NASA. The GE goals for this program are:

- a 10% fuel burn reduction relative to the current industry state of the art represented by our GE90
- a 10dB noise reduction
- a further 20% reduction in NOx relative to the GE90 and
- a 50% reduction in operating costs

Big challenges! To accomplish these goals we will have to attack every engine component for radical improvements as shown in Figure 3. We are starting by significantly increasing the pressure ratio from 42, to 55-60. We will raise the temperatures in the engine by 100°F at the exit of the compressor, and 200°F at the turbine inlet for improved performance. At the same time, we will reduce the stage count from 22 to 15 to



	Baseline State-of-the-Art	UEET
PR_{an}	1.55	1.50 to 1.70
$PR_{an\ Hub + Booste}$	1.80	3.0
$PR_{Ove\ a\ l\ at\ OC}$	42	55 to 60
BPR	8.4	8 to 10
T_3 (°F)	Base	+100°F
T_4 (°F)	Base	+200°F
Stage Count	1/3/10/2/6	1/3/6/1/4

Figure 3. Ultra Efficient Engine Cycle.

lower maintenance cost. We intend to redefine the state of the art.

We plan to develop a 20 to 1 pressure ratio, single stage turbine core. We see that core going into:

1. A military transport engine with a bypass ratio of 8 to 10.
2. A long range bomber engine with a bypass ratio of around 2.
3. A destaged compressor allows insertion in a long-range fighter engine with a bypass ratio of around one.
4. It could also be applied to a Turbine Combined Cycle engine for Mach 4 to 6 applications.

On the commercial side, it makes an ideal application for a commercial turbofan at a bypass ratio about 10. It could be used in a Supersonic Business jet with a variable fan design.

It could also be the nucleus for a Marine and Industrial engine application for power generation. This advanced technology machine fulfills our future needs in a multitude of applications

Figure 4 shows that we are looking at:

- a high speed swept fan with suction side bleed,
- case treatment in the booster for improved stall margin,
- a 20 to 1 pressure ratio 6-stage compressor,
- a high delta-T ultra low emission combustor with ceramic matrix composite liner,
- a single-stage 5.5 pressure ratio high-pressure turbine,
- a counterrotating low pressure turbine,
- non-deteriorating low leakage seals,
- advanced materials,
- robust high speed bearings, and
- advanced diagnostics.

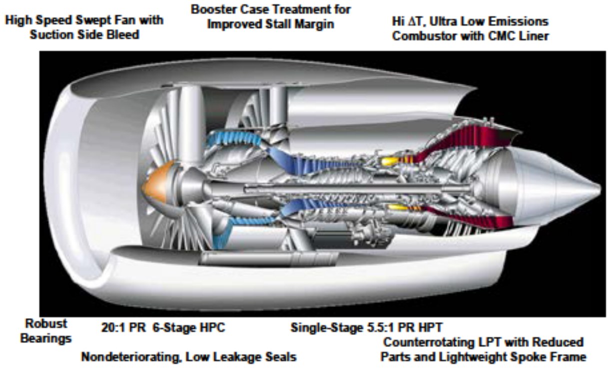


Figure 4. Ultra Efficient Engine Technologies.

This engine will indeed transform the state of the art. It's obviously not around the corner, but we are developing these technologies now to enable us to get there. It permits us to focus our efforts on the right technologies and incorporate our findings in our products.

2 vs. 3-Shaft Machines. We strongly believe that in the foreseeable future, the optimum commercial engine architecture is a 2-shaft, direct-drive, high bypass ratio (that is 8 to 10) machine. We do not believe that 3-shaft or gear-driven fan engines offer any benefit at this time. I will explain why! Let me start with a 2 versus 3-shaft comparison. A direct comparison of an Engine Alliance GP7200 and a Trent 900 engine shows both engines incorporate a 116" diameter fan. Figure 5 indicates the GP7200 incorporates 2 shafts while the Trent 900 utilizes 3 shafts. Our comparison indicates that the engines have the same length. The GP7200 has: 3 less stages than the Trent; incorporates one less frame; has 5 bearings opposed to 7, and has one hot sump opposed to 2. Bottom line, the 2-shaft machine is simpler and should be more reliable all the way around.

Let us now look at weight. A propulsion system comparison for the 747-airplane application indicates that the 3-shaft engine is indeed 300 pounds heavier

	GP7200	RR Trent 900
Engine Length, inches	179	179
Number of Shafts	2	3
Number of Stages	19	22
Number of Frames	3	4
Number of Bearings	5	7
Number of Hot Sumps	1	2

Figure 5. 2 vs. 3-Shaft Engine Comparison.

than the GE machine. A comparison on the A330 shows again, that the Trent is a 100 pounds heavier. Looking at future engines, the latest Rolls engine, the Trent 900, is about 125-lbs. heavier than our 2-shaft machine, the GP7200. When we look at the propulsion systems designed in our industry (Figure 6), we find that weight is primarily driven by the fan diameter. Their relative position on the curve is very much a function of execution.

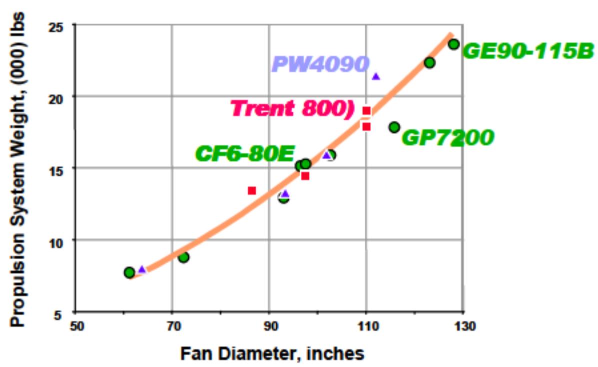


Figure 6. Engine Weight Trends.

A compressor matching comparison between the GP7200 and a Trent 900 shows that a 2-shaft machine has a higher pressure ratio for fewer number of compression stages, achieves lower loading, and obtains better efficiencies. Figure 7 shows we are better matched on a 2-shaft machine for better performance and operability. Reliability results speak for themselves. On the A330, the 2-shaft CF6-80E1 has significantly better In-Flight Shutdown, Unscheduled Engine Removal, and Delay & Cancellation statistics compared to the 3-shaft Trent 700.

In summary, 3-shaft designs require: additional speed for stall margin, additional frames, bearings, more

Compressor Matching

	2-Shaft	3-Shaft
Engine Overall Pressure Ratio	42	38
Stage Count	12 - 13	14
Loading	0.65	0.74
Efficiency	0.91	0.90

Figure 7. Compressor Architecture.

stages, and more sumps, therefore, more complication. The 2-shaft machine indeed provides a better product.

Direct vs. Gear-Driven Fans. Our competition has been talking about gear-driven fans for the last 10, maybe even 15 years. We took an in-depth look at a direct vs. gear-driven installation for a 35,000-lb. class engine. We defined a common core and installed a 76" direct drive fan. To achieve the right operating pressure ratio, we incorporated a 6-stage booster and a 6-stage low-pressure turbine. For the gear-driven configuration we employed a slower 76" fan, a 3-stage booster, and a 3-stage low-pressure turbine. There are indeed fewer stages on the gear-driven machine, however, we needed to add a 640-lb. gearbox to drive the fan.

As we first look at the weight (Figure 8), we note that the Fan / Low Pressure Compressor is lighter for the Gear-Driven configuration. The core is the same. The low-pressure turbine is lighter. The controls and accessories are about the same. The nacelle is slightly lighter. So the Gear-Driven machine appears lighter until you add the Gearbox. Then we sit at parity with basically the same weight for both configurations.

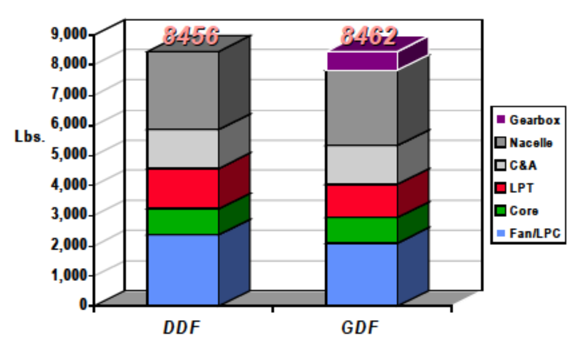


Figure 8. Engine Architecture Comparison.

When we look at fuel burn, we get basically the same result with no inherent performance advantage due to a gear drive. Let us now see in Figure 9 how both designs compare in fuel burn as a function of bypass ratio. You will first note that a minimum in fuel burn is achieved at bypass ratios of about 8 to 10 irrespective of the configuration. As we grow in bypass ratio we significantly loose in fuel burn. By the time we get to a

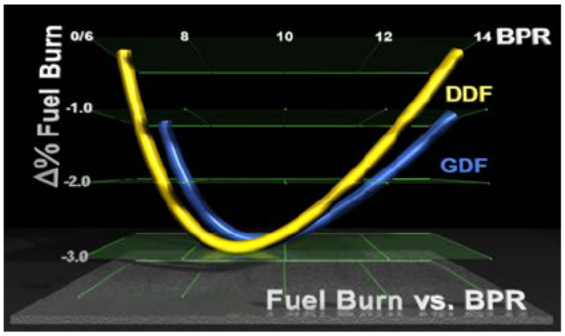


Figure 9. Installed Engine Performance Trends – Fuel Burn vs. Bypass Ratio.

bypass ratio of 14, the gear-driven design offers between a half and a 1% advantage but you have to go there at significant weight and performance penalties.

On noise, no significant difference as shown in Figure 10, if anything the Direct-Drive offers larger noise margins. Both designs offer benefits as you move toward a very high bypass ratio, of course at the expense of weight, fuel burn, and range. In summary, Gear-Driven and Direct-Driven Fans appear comparable in fuel burn, performance, and noise. The conventional direct-drive offers the performance without the reliability issues associated with a gear. This study which I shared with you as well as other studies we performed confirms that the architecture of choice for GE/CFM engines remains a 2-shaft, direct-drive design.

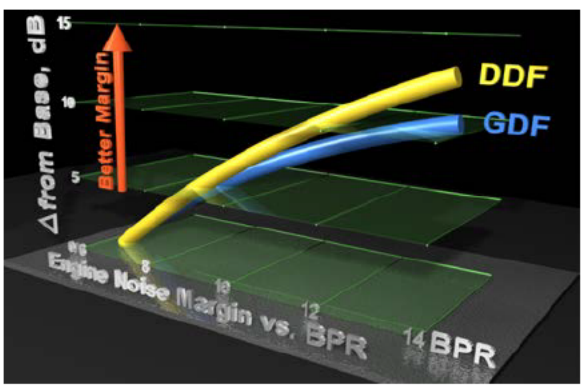


Figure 10. Installed Engine Performance Trends – Engine Noise Margin vs. Bypass Ratio.

Aerodynamics

Let us begin our discussion about the technologies we are working on to permit us to move forward, with fan aerodynamics. We have just completed last year, a series of tests to optimize the fan blade for the GE90-115B engine. The winning configuration (Figure 11) turned out to be a high flow swept fan. With this configuration we exceeded our goals and demonstrated world-class flow and efficiency superior to any in the industry. This represents a real achievement in fan aerodynamics.

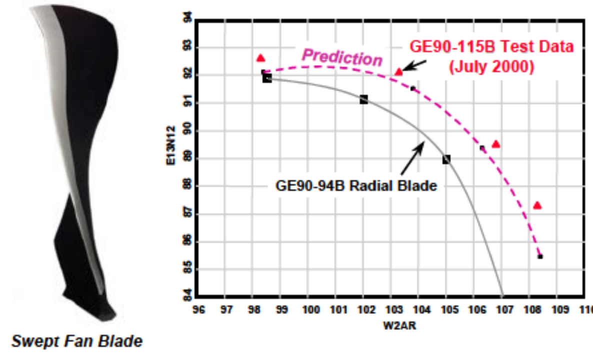


Figure 11. GE90 Swept Fan Blade.

We also tested a 9-Stage derivative of the GE90 Compressor shown in Figure 12. This is the configuration planned for the GE90-115B and the GP7000. Here again we gained about a point in efficiency, exceeding our goals and permitting a significant temperature reduction at takeoff, and improved performance at cruise. We believe that this compressor is setting a new standard for the industry.

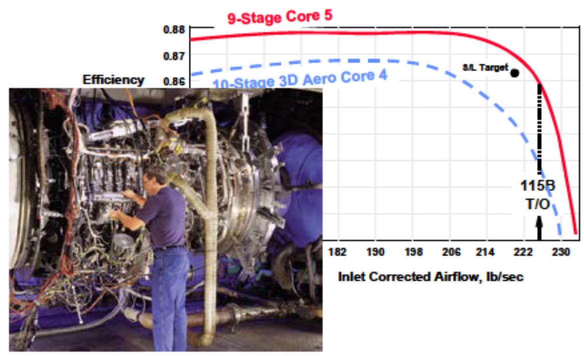


Figure 12. 9-Stage GE90 HP Compressor.

We have been working on the development of a low stage number compressor for the Project TECH56. There we increased the pressure ratio from 11.4 to close to 15 as shown in Figure 13 while reducing the number of stages from 9 to 6. We have reduced the airfoil count by over a third. We ran the first build of the compressor and met or exceeded the stall margin objective, achieved the desired airflow, and experienced low stresses throughout the machine. We are preparing for the second build where we hope to achieve our best efficiency.

	CFM56	*Project TECH56*
Number of Stages	9	6
Pressure Ratio	11.4	14.7
Pressure Ratio per Stage	1.31	1.57
Number of Airfoils	1518	968
Variable Stage Count	4	3

Figure 13. HP Compressor Technology.

Let us now talk about Turbines. We have run a new High Pressure Turbine for the Project TECH56 followed by a new counterrotating low-pressure turbine on our unique Dual Shaft Rig. This represents our third generation single-stage turbine, shown in Figure 14.

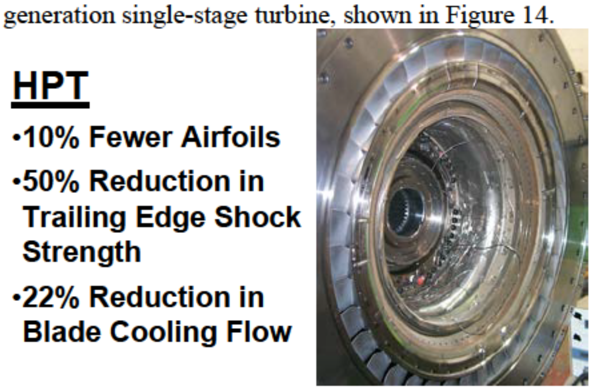


Figure 14. Project TECH56 HP Turbine Technology Features.

The high-pressure turbine was higher in loading, had a 10% reduction in airfoil count, and incorporated new features to reduce the shock strength going downstream. The low-pressure turbine also was highly loaded and incorporated a 19% reduction in airfoils. The high-pressure turbine results (Figure 15) were impressive, exceeding any efficiency ever experienced in a single-stage turbine. We reduced the number of airfoils by 10%, increased the loading by 15%, and improved the efficiency by almost a point. We are very pleased with the results! On the Low Pressure Turbine, we exceeded our turbine efficiency prediction by close to a point while reducing the number of airfoils by 19%. We plan to evaluate additional designs later this year. We are indeed working to set a new standard in low-pressure turbine design.

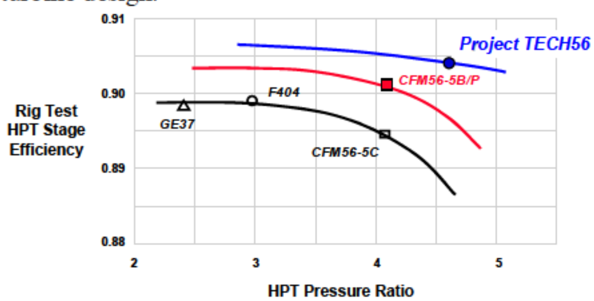


Figure 15. HP Turbine Test Results.

Good seals are essential for good new engine performance as well as for performance retention. As part of the Project TECH56 program, we have been developing Brush Seals for key locations in the High Pressure Turbine and testing them in a full-scale high-pressure rig. Our latest configurations are yielding significant results (shown in Figure 16) with a 40% reduction in leakage. We have cycled these seals

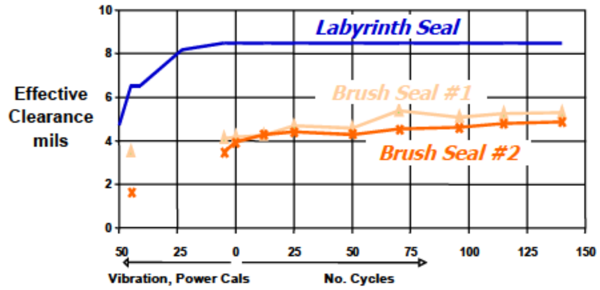


Figure 16. Seal Test Results.

extensively on the rig with no increase in leakage. We are looking here at a 12°C improvement in engine temperature, as well as a reduction in deterioration in service. Significant more time on wing. Very nice results. We are in the process of endurance testing a CFM56 engine with these new seals. We're looking forward to this step-change in technology.

Environment

The environment has influenced our lives in the past and we know that it will in the future. Let us first look at emissions. The key emissions concerns are CO_2 and NOx as they affect the ozone layer and global warming. We have been reducing CO_2 emissions for a number of years as we made our engines more efficient and therefore burn less fuel. We have also been working to reduce NOx emissions as we see stringency increasing (Figure 17) . The ICAO NOx standard first set in 1981, became 20% more stringent in 1996 and will get 16% tougher in 2004. The good story here is that all GE/CFM products <u>already</u> meet all these standards. The fact remains however, that these standards will continue to become more stringent in the ICAO rules and in local communities. So we have to continue to work on reducing emissions.

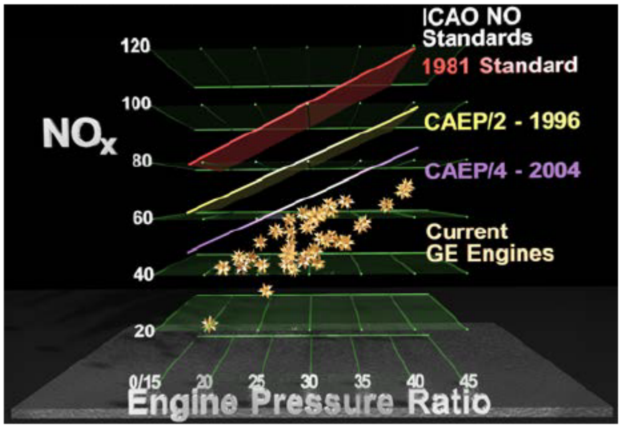


Figure 17. Emissions Stringency Increasing.

At GE we started with a Low Emission Single Annular Combustor which we optimized for the CF6 family. When the environmental pressure in Europe demanded lower NOx, we developed a Dual Annular

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