AirInsight

Breakthrough: The Market Changing Pratt & Whitney Geared Turbofan Engine

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I. Does This Engine Change Everything?

Pratt & Whitney's marketing slogan for their new PurePower™ PW1000G geared turbofan ("GTF") engine reads "This Changes Everything." It may be an appropriate tagline for both the new engines as well as for the outlook of Pratt & Whitney ("PW") as a company. PW was at one time the most dominant player in commercial aircraft engines, only to lose their market leadership to the CFM International over the past two decades. After an rather long 20 year period of research and development on a new architecture proved fruitful, PW is now poised for a market share rebound through the introduction of innovative, game changing technology.

Figure 1: Pratt & Whitney PW1000G Engine Prototype on Test Aircraft[1]

The PW PurePower™ 1000G geared turbo-fan, commonly called the GTF, will be the first of the "next generation" of aircraft engine to enter service. This engine differs from conventional engines because it introduces a gear between the fan and engine core, enabling each section to run at a more optimal speed. Compressors and turbines are more efficient when rotating at higher speeds, while fans are more efficient and move more air at slower speeds. The insertion of the gear enabled engineers to optimize the performance of the fan and engine core using different

[1] Photo credit: Pratt & Whitney

speeds. In conventional jet engine architectures, a single shaft turns the fan and engine core at a single speed that is a compromise between the optimal speeds for the fan and core.

The Gear Changes Performance

This new architecture results in substantially improved fuel efficiency and environmental performance, while at the same time lowering maintenance costs. The GTF has 16% better fuel economy than current generation engines, and a 75% reduction in noise.[2] This engine is providing a step-function improvement in both efficiency and environmental performance.

Through its innovative architecture and patented gearbox design, the GTF utilizes fewer stages to achieve the same performance levels as engines with more conventional engine architectures, and does this at lower temperatures and pressures. Fewer parts and cooler temperatures generate lower maintenance costs and better operational reliability.

Perhaps the most important aspect for this engine is the potential for future performance improvements. With a change in gear ratio and enhancements to the engine core, PW believes an additional 10-15% improvement in fuel burn can be achieved over the next decade. Such a radical level of improvement, 26%-31% over today's engines, will be an economic game-changer. The competing CFM LEAP engine, constrained by conventional engine design, is reaching the limits of potential performance from that architecture and is unlikely to achieve similar performance growth over the next decade.

Selected for five aircraft programs with 12 different model variants, the GTF has already secured commitments for more than 6,000 engines for the Bombardier CSeries, Airbus A320neo, Mitsubishi RJ, Yak-242 (formerly Irkut MS-21), and Embraer E2 programs.

[2] Source: Pratt & Whitney estimates, confirmed by flight tests at Bombardier

The GTF is currently offered in three size ranges, from 15,000 to 17,600 pounds of thrust, from 18,900 to 23.300 pounds of thrust, and from 28,000-35,000 pounds of thrust. Because the engine is designed to be scalable, the size of an engine could potentially be increased to the 75,000 to 100,000 pounds of thrust class for wide body applications within a short development period.

Imitation is the Sincerest Form of Flattery

Several years ago, when Pratt & Whitney first introduced the geared architecture concept, the aero engine industry was skeptical of geared architecture. PW's two main competitors in commercial engines, General Electric and Rolls Royce, raised questions about the reliability of a gearbox operating at the thrust levels used by commercial airline engines. They asserted that the proven conventional architecture would provide equivalent performance with less risk.

Geared turbofans have been used before on smaller engines, but never reaching thrust levels required to power a larger aircraft. PW had been studying geared architectures for 20 years in their R&D laboratory, but were met with limited results until a breakthrough they designed that enabled a lightweight, yet reliable, gear system.

With only seven moving parts, PW's gearbox design enables engine optimization with both reliability and simplicity in maintenance. The elegant simplicity of the design, combined with low maintenance requirements has resulted in the industry gaining confidence in the technology.

Gears are not new, nor is their use in aircraft engines. Every turboprop engine is geared, as are turbine engines on helicopters. Within United Technologies (which owns Sikorsky), United Technology Aviation Services (formerly BFG and Hamilton-Sundstrand) and Pratt & Whitney, the group has experience with more than 75,000 gearboxes operating for more than a billion flight hours. Leveraging that experience in the gear design for the GTF enabled PW's confidence in their technology, and their ability to develop a reliable application.

Today, with the program approaching 10,000 hours of flight and ground testing prior to entry into service, the reliability and durability of the gearbox are no longer a concern for airline customers. Because initial test results have verified the fuel economy and environmental gains, the competition has taken notice.

Rolls Royce recently announced that it will utilize a geared configuration in its next generation Ultrafan™ engine, and SNECMA (a joint venture partner with GE in CFM International) is now evaluating the potential for a geared configuration for its next generation engine[3].

The Advantages of a Geared Configuration

A geared configuration enables the fan and engine core to run at their optimal speeds at the same time, rather than a less efficient single speed in a conventional architecture. Greater efficiency results from a higher by-pass ratio that is generated from more air being pushed around the core by the fan, which operates at a lower and more efficient speed. The core is also more efficient, as turning at higher speeds, it requires fewer engine stages to produce the same level of thrust. The fewer stages directly translate to lower material and maintenance costs for operators.

When compared to a conventional engine, the GTF has a noticeably larger fan, but a smaller engine core. This results in significantly lower noise levels than today's engines, with decreases of 15-20 decibels. Fifteen decibels doesn't seem like such a large number, but because the decibel scale is logarithmic, doubling every ten decibels, a reduction of 15 decibels translates to a 75% reduction in noise. Imagine hearing only 25% of the noise level of existing engines, and what that means for people who live near airports. The low noise performance of the GTF is phenomenal.

At the first flight of the Bombardier CSeries dignitaries at the viewing stand were positioned halfway down the runway to observe the first flight. A business jet to photograph the event preceded the takeoff of the GTF

[3] http://aviationweek.com/awin/rolls-royce-reveals-next-gen-engine-plan-0

equipped CSeries. Shortly thereafter the eagerly awaited take off occurred. The CSeries was so quiet that many observers didn't realize that the aircraft was coming down the runway until it was nearly in front of the reviewing stands and in the air. Environmentally, this engine is a paradigm shift.

What the GTF Means for Aviation, Consumers, and the Environment

For airlines, each new generation of engine technology has presented a trade-off. Airlines could gain better fuel efficiency with new generation engines, but would incur higher maintenance costs, due to the higher temperatures and pressures with the improved engines. The GTF may be the first new generation engine to eliminates that trade-off, offering improved performance while maintaining maintenance costs at or below current levels, because the gearbox enables a smaller core with fewer parts.

For passengers, a more fuel-efficient aircraft translates to lower costs and continued competitive prices for air travel.

The environment benefits from a smaller carbon footprint. Using 16% less fuel, results in 16% lower carbon emissions and, through new burner technology, lower NO_x emissions.

For those living near airports the 75% reduction in noise levels from the GTF will certainly be welcomed. With this aircraft, the highest noise concentrations will remain within the boundaries of the airport, rather than over adjacent houses and businesses. It should also allow some airports to lift nighttime operational limits. This potentially provides more airline operations, more consumer choices and of course, more jobs.

The bottom line - it does appear that the PW1000G is truly a game changing technology.

II. A Configuration for the Future

Recognizing that the current engine architecture will peak over the longer term, engine manufacturers have been examining alternatives. PW believes the geared configuration will provide substantial benefits, while GE and Rolls Royce have focused much of their R&D on “open rotor” concepts.

Open rotor engines are essentially a blend of a jet and turboprop, with a large curved propeller that is not shrouded by a nacelle. These concepts would generate 35% fuel efficiency improvements over today’s engines.

However, open rotor concepts, while interesting, have practical difficulties for applications on today’s aircraft. The engines are quite large, and would need to be mounted above the wing to provide ground clearance for the larger propellers. In addition, aircraft speeds would need to be reduced, and noise attenuation is a key problem. As a result, open rotor concepts were viewed as a potential “next generation” solution for the 2025-2030 time frame.

PW chose a different path than their competition, focusing on the advantages of the geared configuration. The architecture of the GTF engine differs from conventional engines, introducing a gear to enable the fan at the front of the engine and the engine core to run at different speeds. That change enables each section of the engine to run at its most optimal speed. A diagram of this technology is shown in Figure-2.

With a larger fan, that turns slower to move more air, the GTF benefits from additional bypass air and propulsive efficiency, enabling lower fuel burn. A rule of thumb is the higher the bypass ratio, the better the fuel economy. With a bypass ratio of 12:1, the GTF will have the highest bypass ratio of any commercial engine to date, and marks a clear advantage over its new technology competitors.

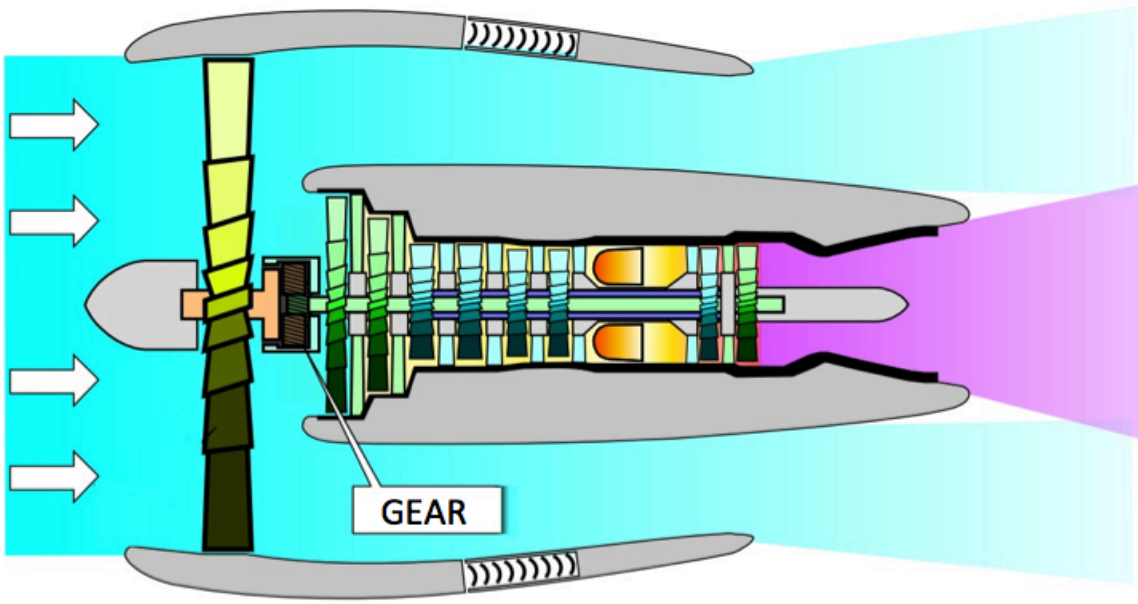

Figure 2: Configuration of Geared Turbofan Engine and Position of Gear between Fan and Engine Core.[4]

A Geared Turbofan is Not a New Concept

Several business jet engines, including the Honeywell (formerly Garrett) TFE-731, have used a geared configuration in low thrust operations. The key breakthrough for Pratt & Whitney was designing a gearbox with the capability to handle large high thrust engines without adding significant weight. PW found a way to extend the concept from smaller engines and to provide a lightweight solution to handle the high thrust levels needed to power large commercial aircraft. The geared architecture provides several important benefits, which PW have taken to new levels, and represents one more stage in the evolution of jet engines for commercial aircraft.

How a Jet Engine Works

Fundamentally, a jet engine works like a balloon filled with air. Thrust is created from the air pressure at the back of an engine that propels an aircraft forward, just as a balloon full of air is propelled forward when released.

[4] Image adapted from Wikimedia Commons, author Tosaka

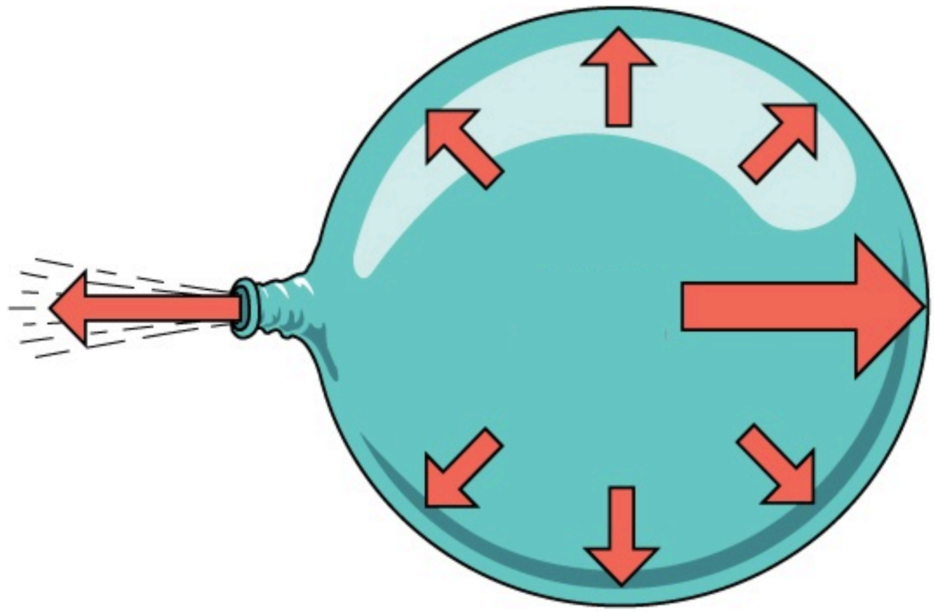

***Figure 3: How a Jet Engine Works*[5]**

Of course, once a balloon runs out of air, it will cease producing thrust. A jet engine works by taking air into the front of the engine, heating it to create air pressure, and exhausting that heated air out the back.

Turbojets

First generation jet engines, or turbojets, featured a closed system, with all of the air from the intake going through the turbines, as shown in the illustration below. These engines were first developed during the late 1930s and entered service during World War II on military aircraft in Germany and the UK.

A turbojet brings in air at the front of the engine, compresses it, ignites it, and uses part of the power to drive the turbine and compressors, and the remainder to propel the airplane forward with thrust.

[5] Source: Encyclopedia Britannica, with modifications.

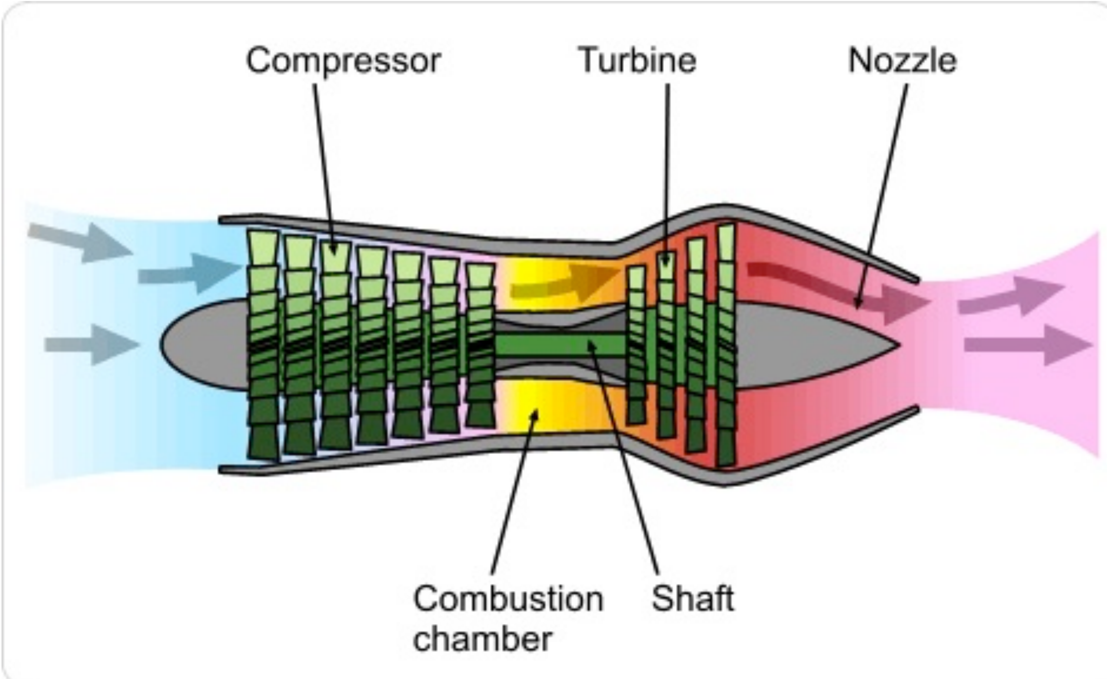

Figure 4: The Configuration of a Turbojet Engine

Low-Bypass Turbofans

The second generation of jet engines introduced a new concept, the turbofan engine. In these engines, a fan is used to direct intake air both through and around the core of the engine. The larger fan in front of the compressor provides direct propulsive energy that bypasses the core, combining it with the air that is pressurized and heated within the engine core to produce more thrust. Turbofan engines, as a result, are more efficient and quieter than turbojet engines. The ratio of the amount of air going around the engine rather than through the core is called the bypass ratio. Early turbofans had bypass ratios that ranged from 1:1 to 4:1

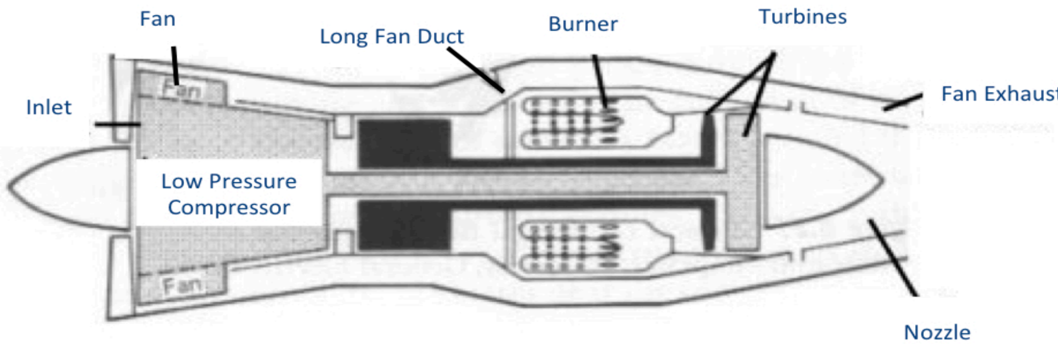

Figure 5: Diagram of Low Bypass Turbofan

High-Bypass Turbofans

In the 1990s, high bypass turbofan engines were introduced and became the current generation of aircraft engines. A typical engine, as shown in the diagram below, has a bypass ratios from 5:1 to 9:1. The larger fans have been installed to provide additional bypass air at the front of the engines, thus improving fuel economy.

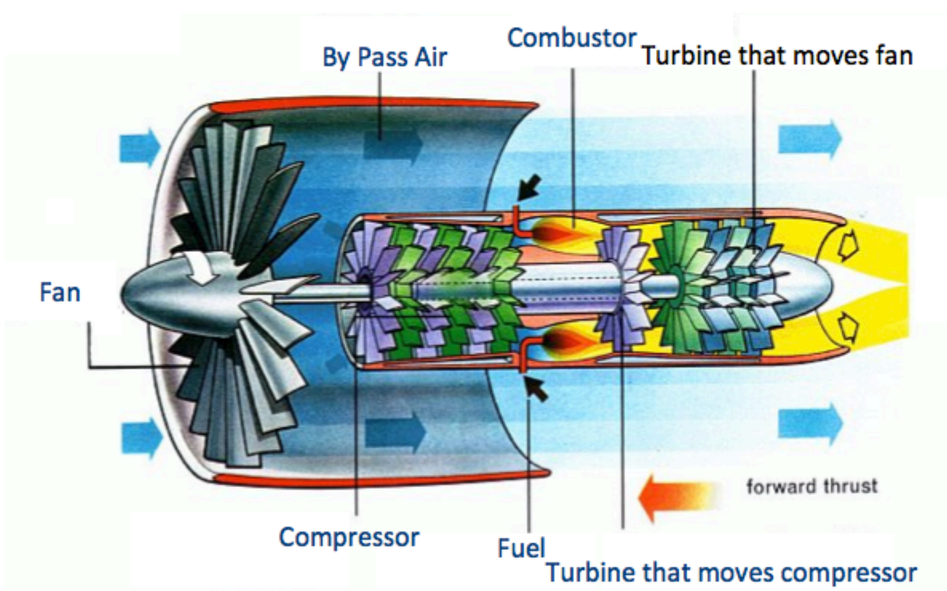

Figure 6: Illustration of a High Bypass Turbofan

The Emerging Very-High Bypass Turbofans

The first of the new generation of aircraft engines is now being introduced. Pratt & Whitney has taken engine bypass ratios to a new level, 12:1 with its GTF engine. This is the result of a larger, but slower turning fan that provides additional bypass air. Because bypass air does not need to be heated, the rule of thumb is the higher the bypass ratio, the better the fuel economy of an engine.

Using a 3:1 gear ratio in the GTF (likely increasing to 4:1 in future versions), the fan is able to turn at a slower speed, while the core rotates faster, enabling the engine to deliver the same performance as a conventional high bypass turbofan with fewer airfoils.

Interestingly, the rotational speed of the core of the GTF, leveraging the 3:1 gear ratio, is the same speed that the first low bypass turbofans operated at. Those engines, such as the PW JT8D that powered the Boeing 727, Douglas DC-9, and other aircraft built from the 1960s through 1980s, demonstrated that higher rotational speeds are not a reliability issue, as those speeds, before the introduction of larger fans, were commonplace.

Future generations of GTF engines will take bypass ratios from 12:1 to between 15:1 and 18:1, likely utilizing a higher gear ratio of 4:1 to further optimize performance, and provide 10-15% better fuel efficiency than the first generation GTF engines that will be installed on the Bombardier CSeries and Airbus A320.

A significant benefit of a geared configuration is that it enables a simpler and more efficient engine core. By increasing bypass air, proportionally more thrust is generated from that source than the thermal energy of the core. Because the core can rotate faster, a smaller core can accomplish similar work, resulting in fewer stages in the compressors and turbines. Fewer stages mean reduced complexity, and because there are fewer parts to replace, lower maintenance costs.

Most economic analyses of the current generation of engines using conventional architecture show a trade-off -- the engine with the lowest fuel burn was typically slightly higher in maintenance costs. This was true for the PW2040 versus RB211-535E4 on the Boeing 757, as well as for the IAE V2500-A5 versus the CFM-56-5 on the Airbus A320 family.[6]

Airbus' economic analysis of the GTF against its competitor, the CFM LEAP (which uses conventional architecture), shows both a fuel burn and maintenance cost advantage in favor of the GTF. In this instance, no trade-off is required, as one engine leads in both of these important categories. As a result, we would expect, all things being equal, for the GTF to gain a 60/40 market share advantage over the CFM LEAP in the long term as engines are chosen for the Airbus A320neo and A321 neo series.[7]

[6] Analysis of US DOT Form 41 data and performance and cost estimates from aircraft manufacturers
[7] Based on AirInsight estimates of operating and maintenance costs, and superiority of GTF over LEAP on A321 application

III. The Innovative Technology Behind the GTF

The GTF is a new technology engine, both in terms of configuration and virtually every element of the engine from the fan at the front of the engine to the low pressure turbine at the rear, leverages advanced technology. In this section, we will examine the technologies utilized in the GTF and the benefits they bring.

The Fan

The visually most striking aspect of the GTF is the size of the fan in relation to the engine core. To produce additional bypass air, larger fans are required to move additional air outside the core within the engine nacelle. As a result, the GTF core appears quite small when compared to today's engines.

Beyond the larger size, advanced technologies are used in both the design and manufacturing of the 18 blades that comprise the fan. PW chose a bi-metallic fan blade, made from a proprietary lightweight Titanium-Aluminum alloy that enables the manufacture of very precise and sharply contoured fan blades. For the GTF, the complex blade shape features four separate and unique curves that optimize performance.

The four specific contours of the fan enable more air to be pushed using the same input energy, improving propulsive efficiency while using less fuel. The characteristics of the design led to the choice of the Titanium-Aluminum alloy from a manufacturability perspective.

In evaluating the design trade-off between choosing metallic or composite materials, the ability to achieve the desired shape and curves using metal was the deciding factor over using composite materials. The metal alloy enabled the use of very thin blade shapes that would be much more difficult to manufacture using composite materials.

As is the case with most new technology engines, the fan is enclosed in a lightweight carbon fiber fan case to reduce overall engine weight.

With a fan larger than conventional engines, the GTF can achieve higher bypass ratios. Today's narrow-body engines have bypass ratios in the 5:1 to 7:1 range. The 12:1 bypass ratio of the GTF will provide a dramatic increase in fuel economy.

While larger fans improve bypass ratios, there are limits as to how large a fan can be accommodated. Larger fans are more efficient, but they are also heavier and induce more aerodynamic drag. PW engineers analyzed the impacts of fan size, drag, and weight on performance, before finding the optimal point in fuel economy for the GTF.

The fan for the PW1135G-JM engine set to be installed on the A321 is 81 inches in diameter, compared with a 63.5 inches for the current V2500 for the same airplane. The 27.5% increase in fan size enables the significantly higher bypass ratio and consequent improvement in fuel efficiency.

The Gear

The component that differentiates the GTF from other engines is the gear itself. The gearbox is comprised of only seven moving parts, using journal bearings that will only require nominal maintenance. The gears are arrayed in a star pattern, with five gears surrounding a center gear, and a ring gear at the outside of the gearbox that moves the fan at a slower speed, as shown below:

Figure 7: Photo of PW1000G Gearbox[8]

[8] Source: Pratt & Whitney

The beauty of the PW design is that the gearbox actually floats within the engine. Positioned just behind the fan shaft the "floating" gearbox is isolated from the case loading and shaft bending within the engine, enabling the gearbox to operate without any misalignment that could cause wear on gear teeth. This ensures a long-life for the gearbox with high levels of reliability.

Designed for extreme conditions, the gearbox also includes back-up lubrication systems that activates should the airplane achieve unusual attitudes, even flying upside-down. That system will ensure proper lubrication in all potential flight regimes. Interestingly, during high angle of attack flight- testing at Airbus, those backup systems never needed to be activated, as the regular system worked well.

Pratt & Whitney has developed an elegant engineering solution for the gearbox that opens up new possibilities for engine performance.

The Core

The PW1000 PurePower engine (GTF) has gained market attention and acceptance for its innovative gear-drive system. The other innovative technologies in this engine, particularly in the all-new core, have not received the same publicity as the configuration changing gearbox. However, as an integral element of the "game-changing" performance Pratt & Whitney touts for this engine, the all-new core of this new engine should not be overlooked.

True Scalability

Perhaps the most interesting innovation for this new core is scalability. The scalability of the new core enables Pratt & Whitney to offer a variety of thrust ranges for different aircraft applications without a redesign, by simply rescaling the specifications using today's computer generated design tools.

Pratt & Whitney could easily scale the PW1000G series to more than 100,000 pounds of thrust for wide body applications with minor modifications to the existing designs. For example in speaking with PW's Bob Saia, he explained that using the gear, a core the size of the PW2000 (as used on a 757), mated with a 145-inch fan could generate over 100,000 pounds of thrust[9]. This would mean an engine in the 777 size class. Scalability enables an aircraft manufacturer to specify a thrust level, and PW can develop an engine optimized for that application by scaling the basic design.

Optimized Core Operating Speeds

In recent years, with ever larger fans providing higher and higher bypass ratios and better fuel economy for today's engines, their internal core rotational speeds have slowed. Large fans can move higher volumes of air at slower speeds, and to accommodate these larger fans, a compromise between propulsive efficiency and thermal efficiency had to be made, slowing the speed of conventional engines as fans became larger. While slowing speeds slightly helps fan performance, it detracts from core performance. With the gearbox, that compromise is unnecessary as the fan can turn slowly while the core rotates at higher speeds.

Of course, this raises the question of higher rotational speeds impacting engine wear and maintenance costs. Will the increase of core speed have a negative impact? The answer to that question is no, as the increase in speed offered by the GTF brings this engine back to essentially the same rotational speeds that the well proven JT8D low bypass engine operated at in its applications for the Boeing 727, Douglas DC-9 and many other models.

PW's experience with engines turning at that speed, combined with advances in materials and design, generates confidence that the new core can handle higher rotational speeds with excellent reliability and with negligible additional wear and tear to components. But accomplishing this task required designing components tailored to higher rotational speeds and optimizing airfoil designs to be most efficient at those speeds.

[9] Interview at http://airinsight.com/2014/05/21/pw-media-day-2014-bob-saia/#.U7vxDCgg75E

Designs for higher speed airfoils must differ from those in conventional engines, as higher speeds generate higher centrifugal loads. New designs were needed for outer shrouds, airfoils and blade roots, with a particular focus on flanges and hubs, to ensure that potential stresses from higher centrifugal force are eliminated. By optimizing speed, PW has been able to increase the specific output per rotation, without the need to increase the number of stages in each engine section. This results in lower weight, and a shorter engine length, as well as fewer parts for lower maintenance costs.

If one starts at the front of the GTF engine and moves backward, there are many features that have been overshadowed by the gear that are worth noting:

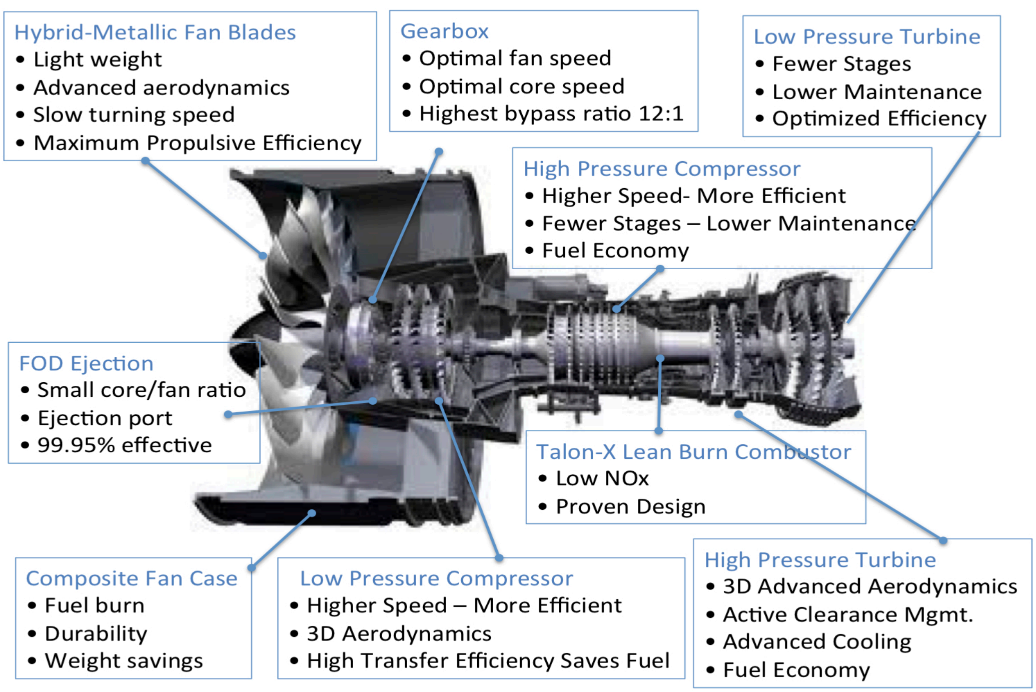

Figure 8: Diagram of Key Features on the PW1000G Engine

FOD Ejection System

Foreign Object Damage ("FOD") occurs when foreign objects, such as gravel or other debris, are sucked into the engine airflow. This can damage internal engine components, which are costly to repair. To counteract FOD, engine manufacturers now utilize designs that eject particles out of the airflow entering the engine core, thus avoiding damage.

The GTF has a FOD-free core design, with an ejection point for foreign objects in the low-pressure compressor that centrifuges particles outside the flow path, and is more than 99.95% effective. Combined with the larger fan size and smaller core opening, the GTF series is extremely effective at FOD rejection and is virtually a FOD-free core, reducing maintenance expense.

Low Pressure Compressor

Three dimensional airfoil shapes are drive efficiency in the low-pressure compressor, which turns at higher rotational velocities to generate increased pressure. Gains in transfer efficiency from the gear have been combined with aerodynamic improvements made possible by new technology airfoils, designed using computational fluid dynamics. With higher rotation speeds, the design of airfoils has been adapted to accommodate higher structural loading of the airfoils and discs on which they are placed. PW has designed its blades and rotors to avoid stress peaks and eliminate the need to "beef-up" components, thus reducing weight.

High Pressure Compressor

PW has been able to gain the same level of efficiency from its engine with fewer stages in the high-pressure compressor due to increased rotational speeds and improved airfoil aerodynamics. These aerodynamic improvements are made possible through three dimensional computational fluid dynamics techniques. Using primarily bladed disks ("blisks"), the advantage of higher rotational speeds eliminates the need for two stages, which dramatically reduces the number of parts. This, all things being equal, should translate to lower maintenance costs for this section of the engine.

Talon-X Lean-Burn Combustor

The Talon-X lean-burn combustor featured in the GTF is a refined third-generation version of the proven PW Talon combustor. This new design burner, like its predecessor, is a dual axial design and features a shorter axial length and simpler fuel nozzles, coupled with float wall construction. The aerodynamics of the burner were developed using computational fluid dynamics techniques to improve the mixing of the fuel and air. The combustor uses a rich burn-quench lean (RQL) approach, thereby dramatically reducing NOx emissions. This design results in a 50% margin to CAEP/6 standards.

High Pressure Turbine

The high-pressure turbine takes advantage of the latest dual use technologies that PW have developed for their fifth generation fighter engine[10], including advanced cooling technologies. These technologies, which remain the equivalent of a "state secret" at engine manufacturers, enable those companies to reduce the metal temperature of the airfoils while withstanding the higher gas temperatures within the engine. The GTF will have a higher pressure ratio and higher inlet temperatures than today's engines to improve thermal efficiency.

A key to PW's advanced technology is that it provides higher cooling using less cooling air. This enables the engine to operate without a penalty in cycle efficiency that

[10] PW produces the F-135 engine for the F-35 military fighter

typically occurs when additional cooling air is introduced. The technology includes a combination of airflow designs within high temperature areas and specialized coatings that prevent metal from melting from the high gas-path temperatures within the engine.

Low Pressure Turbine

The efficiency of the engine enables PW to only use three stages for its low-pressure turbine, half as many stages as a conventional drive engine would need to yield the same efficiency. This generates a significant savings in parts, and thereby maintenance costs. PW estimates that it will use 46% fewer airfoils in the GTF than today's conventional direct drive engines.

MTU, an engine manufacturer and component suppler, based in Germany, is a development partner on the GTF, and designed the new high speed LPT for the GTF. The design effort focused on balancing a number of design tradeoffs to optimize higher rotational speeds while maintaining low maintenance costs, and improved efficiency. Designs of the outer shrouds, airfoils and roots of the blades have been optimized to accommodate higher speeds, higher pressures, and higher airflow temperatures, all while reducing the number of parts and thereby expected maintenance costs.

INNOVATIVE TECHNOLOGIES

The GTF has a number of innovative technologies that drive the efficiency of this new engine. One of the reasons we don't hear much about these technologies in detail is that PW wants to keep them proprietary. Despite that, we have gained insight into several of the technologies utilized in the GTF engine.

Advanced Manufacturing Technology for Sophisticated Shapes

Pratt & Whitney is among the industry leaders in the application of advanced additive manufacturing technology, currently using 24 parts produced by additive manufacturing on the first GTF application for the Bombardier CSeries. These unique engine components are made by building-up parts from powdered metal, rather than the traditional approach of cutting larger metal pieces.. Using powdered metal, which is sintered using lasers to build layer upon layer, PW is now able to create parts with complex shapes with extreme precision.

Those shapes can be further optimized, with only the metal required for the desired functionality included, thereby reducing weight. In addition, unusual shapes designed to provide just the right amount of cooling air or fuel flow at the exact point when needed can improve the efficiency of the engine without the loss of cycle efficiency.

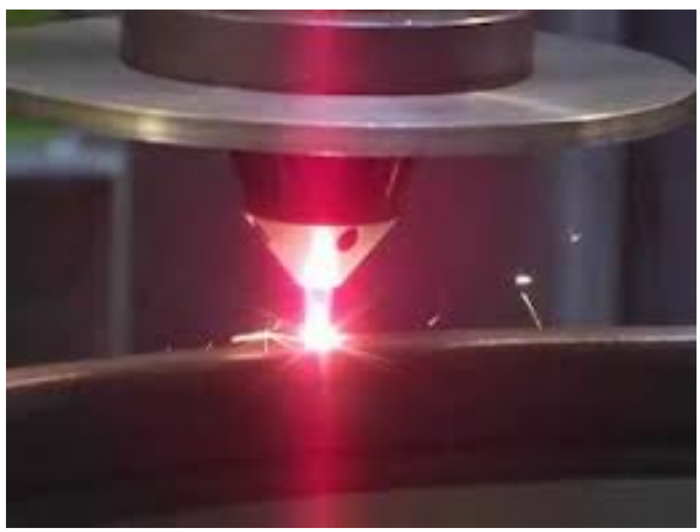

Figure 9: Example of an Additive Manufacturing Process, or 3D Printing of Metal Parts[11]

The benefits of advanced additive manufacturing technology include the ability to generate shapes and passages impossible to create with conventional manufacturing. This allows PW the ability to manufacture to extremely high tolerances, as well as energy efficiency and lower costs.

[11] Laser sintering of powdered metal is one of several 3D printing processes in use at PW

With additive manufactured parts an integral part of the GTF production process, Pratt & Whitney has chosen to vertically integrate. The company produces its own powdered metal alloys and raw materials for the additive manufacturing process. This also provides the company with more extensive quality control over the process of "printing 3D" parts.

The successful implementation of additive manufacturing, a rapidly evolving technology, has spawned re-imagining by development engineers to think in terms of what is possible to build-up, rather than cut. Because shapes and flows can be optimized with minimal materials, some of the applications for additive manufacturing include parts that look completely alien to those manufactured using traditional machining methods. The real benefits of additive manufacturing will likely be increasingly seen in the second generation GTF, after engineers explore the full potential of this new technology.

State of the Art Cooling Technologies

The one area that remains a highly guarded secret for engine manufacturers is how cooling technologies are used to reduce metal temperatures in order to withstand the ever-rising gas path temperatures in the combustor and turbines. PW has access to dual-use technology for engine cooling, as proven with their fifth generation fighter engine design for the military, an engine with the hottest engine temperatures of any in production.[12] Some of that technology has been adapted for civil use on the GTF, with PW carefully balancing the selection of technologies from a cost and maintainability standpoint.

Advanced coating technologies are at the heart of the cooling process, as these coatings insulate the metal from high temperatures that would otherwise cause it to melt. These cooling technologies enable the engine to maintain higher overall pressure ratios and higher inlet temperatures without resulting in higher metal temperatures and

[12] Dual use technology is paid for by the contractor rather than DoD, enabling the company to utilize technology developments in civilian as well as military applications.

excessive wear to metal components. The proprietary secret at PW surrounds the ability to generate additional cooling with a minimum amount of cooling air, enabling both weight savings and maximizing cycle efficiency.

PW is also quite advanced, as is GE, in the use of ceramic matrix composites ("CMC") for its military engines, as well as a new technology that replaces CMC to provide better cooling, but remains proprietary. Their experience with these technologies will enable its engineers to design the second generation GTF with even higher pressures and temperatures to further improve thermal efficiency.

MANAGING TECHNOLOGY RISKS

The new technologies used in the GTF engine introduce an element of risk, as with any new development. The key to success is how well those risks are managed and mitigated during the development process. Let's examine the risks associated with the GTF engine:

The Gear: Geared turbofans are not something new, as the Honeywell (formerly Garrett) TFE-731 engine, that is used in business jets, is a geared turbofan with high reliability. The innovative breakthrough in design by PW that enables the use of a gearbox in a much larger engine is the key to success. With only seven moving parts, a "floating" design, and essentially no maintenance requirements, those risks have largely been mitigated.

Advanced Manufacturing for Parts: Building up parts using additive manufacturing isn't new, but a large-scale production operation is. PW is among the industry leaders in 3D printing, and is pioneering its use in the new engines. A key risk is whether parts built up from powdered metal will have the same reliability as traditionally manufactured parts. Extensive testing has shown that these computer controlled processes are quite reliable, providing equal to if not more reliable parts. With more complex shapes and lower weight, those 3D printed parts deliver significant performance and economic benefits.

Cooling Technology: The GTF will run at a higher temperature than today's engines, thus requiring advanced cooling technologies. There will be an increase in the use of specialized coatings in this engine, many of which have already been proven successful in the V2500 Select engine. In addition, PWs proprietary cooling technology requires less cooling air, and therefore will not have a penalty in terms of cycle efficiency.

Because those technologies work well, the GTF will not require the use of exotic materials such as ceramics, which are can be very costly to manufacture and maintain. Despite the higher running temperatures, it will have a significantly cooler temperature than a similar performing direct-drive engine, and not require exotic materials for cooling.

Computational Fluid Dynamics: Engineering tools and computing technologies have advanced in recent years, and have been successfully utilized in many aerospace applications. PW integrated the latest CFD tools into their engineering processes, enabling the creation of new airfoil designs that optimize airflow and cooling. The design experience from fifth generation military engines has allowed PW to use leverage technologies for the GTF with very high confidence.

Design for Maintenance: Faced with a competitive disadvantage in maintenance costs on existing products, PW stressed simplicity in the architecture of the new engine, focusing on minimizing the number of parts and engine stages to reduce, rather than increase, maintenance costs. With 1,500 fewer airfoils in an engine, the cost of those airfoils should be reflected in lower maintenance costs. PW has targeted maintenance costs 20% lower than today's V2500 A-5 engine for its GTF of equal thrust.

IV. Aircraft Applications for the GTF

The PurePower 1000G is currently selected for 12 different models within five airframe families, and has more than 6,000 engines currently on order or option. Aircraft families include the Bombardier CSeries, Airbus A320neo, Mitsubishi MRJ, Yakovlev Yak-242 (previously the Irkut MS-21), and Embraer E2 jets.

Bombardier CSeries

The Bombardier CSeries is a new generation passenger jet optimized for the 100-150 seat class. Two models of the aircraft are planned, the CS100 and CS300. The CS100 has seating for 110 in a typical configuration. The CS300, has seating for 130 in typical configurations, but can accommodate a maximum of 160 passengers in an all economy configuration.

Figure 10: Bombardier CS100 at First Flight 16 September 2013[13]

[13] Source: Bombardier Aerospace

The CS300 directly challenges the Airbus A318/319/319neo and Boeing 737-600/700 and -7MAX. The CS100 competes with the Embraer E-190/195 and E2-190 and E2-195 and Sukhoi Superjet. Bombardier claims substantially better economics for its aircraft in comparison to the current and planned Airbus, Boeing and Embraer jets. The first flight of the CSeries occurred in September 2013, but the program has since experienced several delays. Entry into service is now scheduled for the second half of 2015.

Bombardier has several major customers for the CSeries, including Republic, Swiss, Korean Air, Gulf Air, Malmō Aviation, AirBaltic, Iraqi Airways, Saudi Gulf Airlines, Odyssey Airlines, and leasing companies LCI and Ilyushin Finance.

Bombardier claims the CSeries will have substantially better economics than its peers, including the re-engined A319neo and 737-7MAX because it will be lighter, and therefore more fuel-efficient. The CS300 is expected to be 12,000 pounds lighter than the similar sized A319neo.

Airbus A320neo

The A320neo (for "new engine option") family , consists of three models, the A320neo, A321neo, and A319neo. The first application, the A320neo, is scheduled to enter service in 2016.

The A320neo family will offer a choice of engines, as does the the current A320 program. The Pratt & Whitney 1100G-JM will compete against the CFM LEAP-1A engine on the three aircraft platforms.

As the bestselling single model aircraft in history[14], the A320 family has a strong following among airlines, many of whom have ordered the neo model to augment or replace their existing fleets. As of June 2014, prior to the Farnborough Air Show, the order book for the A320 neo family shows orders for 2,702 aircraft, with another 1,113 options. These include 45 A319neo, 2,103 A320neo, and 554 A321neo.

[14] Source: Jet Aviation Services aircraft database.

Figure 11: Artist's Rendering of A320neo[15]

To date, customers have split the engine orders between the two competitors, with 903 for PW and 867 for CFM. However, 1,073 orders remain without an engine selection, more than 38% of all orders.[16] The competition for those orders is expected to be intense.

While most existing customers for the CFM-56-5 and V2500 engines are likely to continue with their existing providers in order to optimize transition costs, a few "conquests" are likely to occur and will make a difference in market share. We expect PW, given the fuel efficiency and maintenance cost advantage, to gain a 60%-40% market share over the longer term, particularly as continuing improvements leverage the growth potential of the GTF design[17].

The A321neo operators favor the GTF, which offers a 35,000 pound thrust variant for better high and hot performance. Currently, PW leads with a 75% market share

[15] Source: Airbus SAS

[16] Source: www.pdxlight.com/neomax.htm

[17] Based on AirInsight analysis of existing CFM and IAE customers switching engine vendors, and the performance and economic data for each engine.

for the A321neo, which is becoming increasingly in demand as airlines upsize their fleets for better seat-mile economics. With only 45 current orders for the A319neo, it is possible that Airbus may defer, or even cancel this program. Boeing is experiencing a similar lack of demand for its 737-7MAX program.[18] Each of these models are "downsized" models that carry the heavier structure required for their larger siblings. New competitors, the CSeries and E2Jets are designed and optimized for that seating capacity, and the A319neo and 737-7Max are economically uncompetitive.

Mitsubishi MRJ

The Mitsubishi MRJ is a 90 seat regional jet, and the first commercial aircraft to be built in Japan since the NAMC YS-11 ceased production in 1974. Building on the success of the Japanese aerospace industry as a subcontractor to Boeing, Mitsubishi and Japanese suppliers identified an opportunity to enter the regional jet market.

Figure 12: Photo of Initial MRJ Under Assembly[19]

[18] Boeing will not produce the 737-7MAX in BBJ form, leading to industry speculation that it may not produce the -7MAX at all
[19] Photo credit: Mitsubishi Aircraft

The MRJ received a launch order from ANA in Japan for 15 aircraft, and has since received orders for 50 firm plus 50 options from Trans States Airlines, as well as an order for 100 firm plus 100 options from Sky West.

The MRJ will be offered in two variants, the 92-seat MRJ-90 and the 78 seat MRJ-70. To date, all orders have been for the larger MRJ-90 model. The aircraft is expected to have 20% better fuel burn than the CRJ and ERJ competitors already in service.

The program has experienced delays, but recently the fuselage and wings of the first test aircraft were mated and engines installed. First flight for the MRJ is expected in 2015, and entry into service is expected in 2017.

Yakovlev Yak-242

The Yakovlev Yak-242 (*ЯК-242*) was formerly designated the Irkut MS-21. This new aircraft will be produced in Russia in three size variants, and will be a direct competitor to the Airbus A320 and Boeing 737 families. The Yak-242 will utilize the same variant of the GTF engine family that will be used on the A320neo family, providing the most efficient narrow-body engines available for this new Russian program.

The Yak-242 plans three models with seating for 136, 152, and 178 respectively in a two class configuration.. The aircraft will be offered with two engines, the PW1400G for western operators and the Aviadvigatel PD-14 turbofan engines for the domestic Russian market.

First flight is expected in late 2015-early 2016, with entry into service planned for 2017. Major orders include 50 for Aeroflot, 50 for Ilyushin Finance, 50 for Rostekhnologi, 50 for Crecom Burj Resources, 15 for VEB Leasing, 10 for UTAir, 6 for Transaero, 10 for IrAero and 3 for Nordwind Airlines.

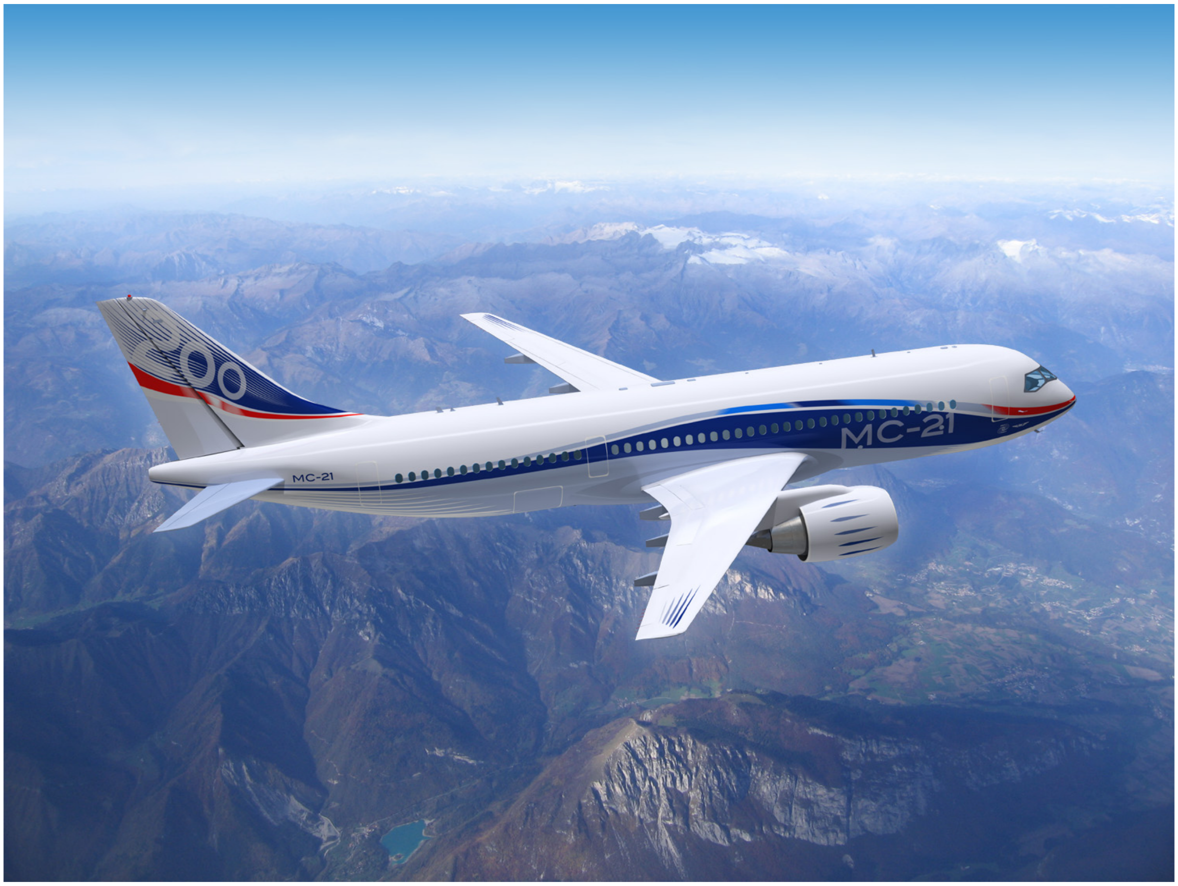

Figure 13: Illustration of Yak-242 (formerly Irkut MS-21-200)[20]

Embraer E2-Jets

The Embraer E2 jets are the second generation of the popular EJet family of aircraft, featuring new engines and a new wing design to improve fuel efficiency. The EJet family, introduced in 2007, is offered in four variants and has been successful in the marketplace, with more than 1,000 aircraft delivered to date.

Facing new competition from the Bombardier CSeries, Embraer decided to re-engine the EJet, choosing the PW1700G and PW1900G for three new models, the E2-175, E2-190, and E2-195. The E2-190 is scheduled for first flight in 2016 and entry into service in 2018, followed by the E2-195 in 2019, and E2-175 in 2020.

[20] Source: United Aircraft Company, Moscow

Figure 14: Artist's Illustration of Embraer E2-190[21]

Seating capacities for the E2-175 and E2-195 will be increased to 88 and 132 seats respectively, with the E2-190 remaining at 106 seats in single class configuration with 31" seat pitch.

Future Aircraft

We expect that Pratt & Whitney will compete for a potential 757 replacement from Boeing or an extended A322 from Airbus should those programs, which are under study, be announced in the near future.

While PW could build a GTF for a wide-body application, the new technology 787 and A350XWB engines have been selected. PW will likely not find a wide-body application for the GTF before 2020.

[21] Source: Embraer

V. An Environmentally Friendly Engine

Environmental concerns impact us all, and air transportation has led the way with dramatic improvements in both carbon footprints and emissions over the last two decades. The GTF will advance those improvements even further, with almost a step-function improvement in emissions and noise levels across the board.

The Pollution Challenge from Jet Engines

Jet engines emit several pollutants, the following being those of primary concern:

- Carbon Monoxide (CO)
- Unburned Hydrocarbons (UHC)
- Particulate Matter (C)
- Oxides of Nitrogen (NO_x)

Carbon monoxide is a toxin that reduces the capacity of blood to absorb oxygen in humans. CO concentrations are quite low from aircraft engines, but CO is not a pollutant that anyone wants to increase in our atmosphere. (Typically, life threatening concentrations typically result from poor furnace combustion and exhaust ventilation inside homes, and not from atmospheric pollution.)

Unburned Hydrocarbons are toxic, and when combined with NO_x can form photochemical smog.[22] There may be some linkage between asthma and small atmospheric particulates. Barium additives are utilized in some aircraft engine applications to reduce smoke, adding another pollutant to exhaust gases

NO_x is a designation for oxides of nitrogen, that result from combustion primarily NO and NO_2. These oxides contribute to photochemical smog, are also related to "acid rain," and can potentially damage plant life. While NO_x emissions from aircraft engines account for less than 2% of all NOx emissions, the location of where the emissions are released

[22] Secondary aerosol formation from photochemical aging of aircraft engine exhaust in a smog chamber, Moracolo, Hennigan, Ranjan, Ngyyen, Gordon, Lipsky, Presto, Donahue and Robinson, Atmospheric Chemistry and Physics 11,4135-4147, 2011. http://www.atmos-chem-phys.net/11/4135/2011/acp-11-4135-2011.pdf

is important. NO_x released at altitude can lead to a chemical reaction that is able to deplete ozone layers in the stratosphere. Reduction of that protective layer in the atmosphere could lead to increases in skin cancers and alter climate patterns.

CO and unburned hydrocarbon emissions have been significantly reduced at low power conditions in today's engines, such as those in cruise flight . This leaves NO_x as the major pollutant in terms of volume. As a result, significant attention has been paid to combustion in modern engines as a source of emissions reduction.

Environmental Regulations for Turbine Engines

The International Civil Aviation Organization ("ICAO") develops regulations for civilian jet engines with more than 6,000 pounds of thrust. Those regulations are based on a landing and take-off cycle for an aircraft, descending from 3,000 feet, landing, and subsequently taking off and climbing back to 3,000 feet. Emissions for that cycle are measured in grams, and are computed by multiplying the Emissions Index (grams/kg fuel) times the Engine Specific Fuel Consumption (kg fuel/hr kN) times the Time in Mode (hrs).

This means there are two ways to influence emissions. The first is to improve combustion in order to reduce the Emissions Index, and the second is to improve the SFC for the engine by reducing the amount of fuel burned. ICAOs Committee on Aviation Environmental Protection has released a series of more stringent standards for commercial aircraft engines.

Addressing NO_x Emissions

NOx is a byproduct of combustion, and is a significant environmental concern. PW has redesigned its Talon combustor in the GTF engine to be more efficient, using a "rich-burn, quench lean" ("RQL") approach.

The underlying principle of the RQL approach is that fuel combustion begins in a fuel-rich zone in which NO_x

emissions are quite low because of low temperatures and limited oxygen. With a rapid quench, the exhaust from the initial burning, into which additional air is quickly introduced, cools significantly so the process can move from rich to lean rapidly. This enables combustion to transition from one low NO_x mode to another low NO_x without generating the high NO_x levels typically associated with a gradual change. In the Talon combustor, this is accomplished by using jets of air that quickly reduce the temperature of the fuel-rich combustion products to a lower temperature at which NO_x formation is negligible.

This is shown in Figure 15, illustrating the "equivalence ratio" of fuel to air against NO_x formation. By engineering the Talon combustor to maintain "equivalence ratios" in the optimal zones as fuel is burned, NO_x emissions can be minimized, as the combustor avoids the middle equivalence ratio zone that causes high emissions, and stays in the "hot dog" shaped zones on either end of the chart.

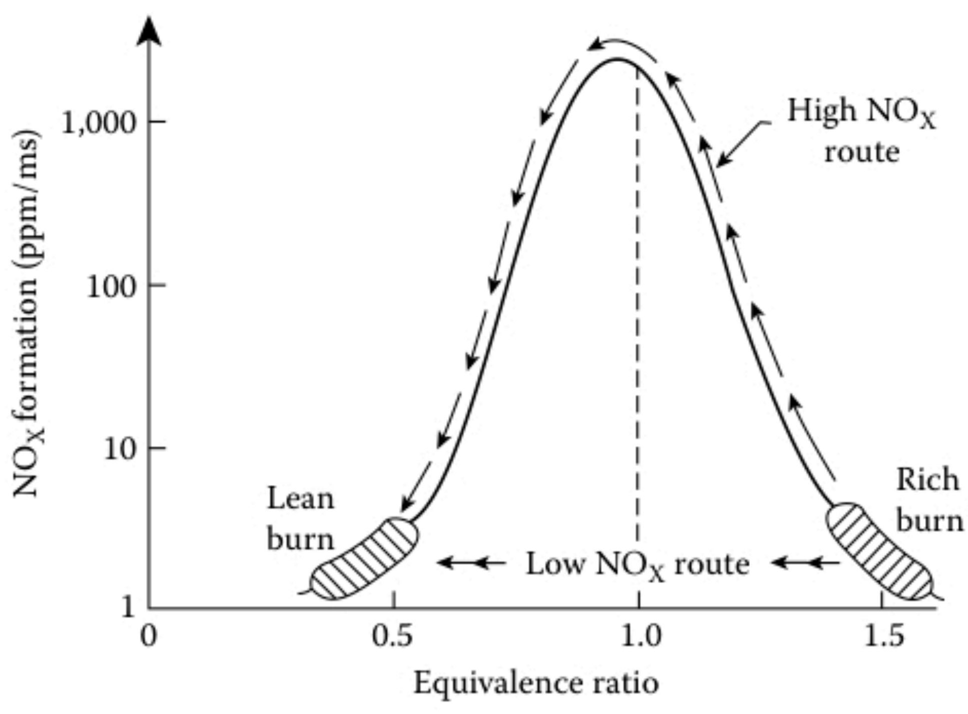

Figure 15: Graph to illustrate the Principle of Rich-Burn, Quick-Quench, Lean-Burn (RQL) Combustion.[23]

[23] *Source: Gas Turbine Combustion, third edition, Arthur H. Lefebvre and Dilip R. Ballal, CRC Press, 2010, page 418.*

This technology balances several challenges.. If temperatures are too high, NO_x formation from thermal sources will increase. But if the temperatures are too low, remaining CO, UHC, and soot may not be consumed. Combined with ensuring that metal parts remain cool, the design of the combustor is perhaps to most critical element in managing engine emissions. Optimizing air flows, fuel mixing, and temperatures across a wide variety of throttle settings, altitudes, and atmospheric conditions illustrate the challenges engineers faced in coming up with an effective design.

The Talon X Combustor, PW's third generation design, is a dual annular combustor using RQL technology with a uniform rich primary zone, quick quench, advanced cooling, and residence time reduction that provides a 70% reduction in NO_x emissions.[24]

Addressing Carbon Emissions

Carbon emissions, including CO and UHC, have been optimized for cruise performance in today's jet engines at very low rates, and become a factor primarily at takeoff.

Because carbon emissions are proportionate to fuel burn, and the fuel burn for the PW1000G is 16% lower than today's engines it will replace, carbon emissions will be proportionally lower.

Noise

Engine noise is a key issue for airlines, particularly at constrained urban airport that adjoin bedroom communities. Noise abatement procedures and curfews are used to mitigate excessive noise levels, often resulting in fines for aircraft arriving late after curfew.

The GTF will reduce noise by 15 decibels when compared with the engines like the CFM-56 and V2500 offered today for narrow-body aircraft. A 15-decibel reduction, on a

[24] *The Pratt & Whitney TALON X Low Emissions Combustor: Revolutionary Results with Evolutionary Technology*, Randal G. McKinney, Domingo Sepulveda, William Sowa, and Albert K. Cheung, AIAA Presentation, January 2007.

logarithmic scale, equates to a 75% reduction in perceived noise levels.

This significantly reduces the geographic area impacted by high noise pollution. The exhibit below illustrates the area impacted by high noise levels with today's engines in use on the A320 and 737 aircraft at New York's LaGuardia airport. It is notable that the noise levels for current engines extend well into Long Island Sound and impact multiple neighborhoods with high noise levels of 75 decibels shown in blue. Very high noise levels, above 90 decibels, in yellow, extend approximately two miles from the airport into Queens.

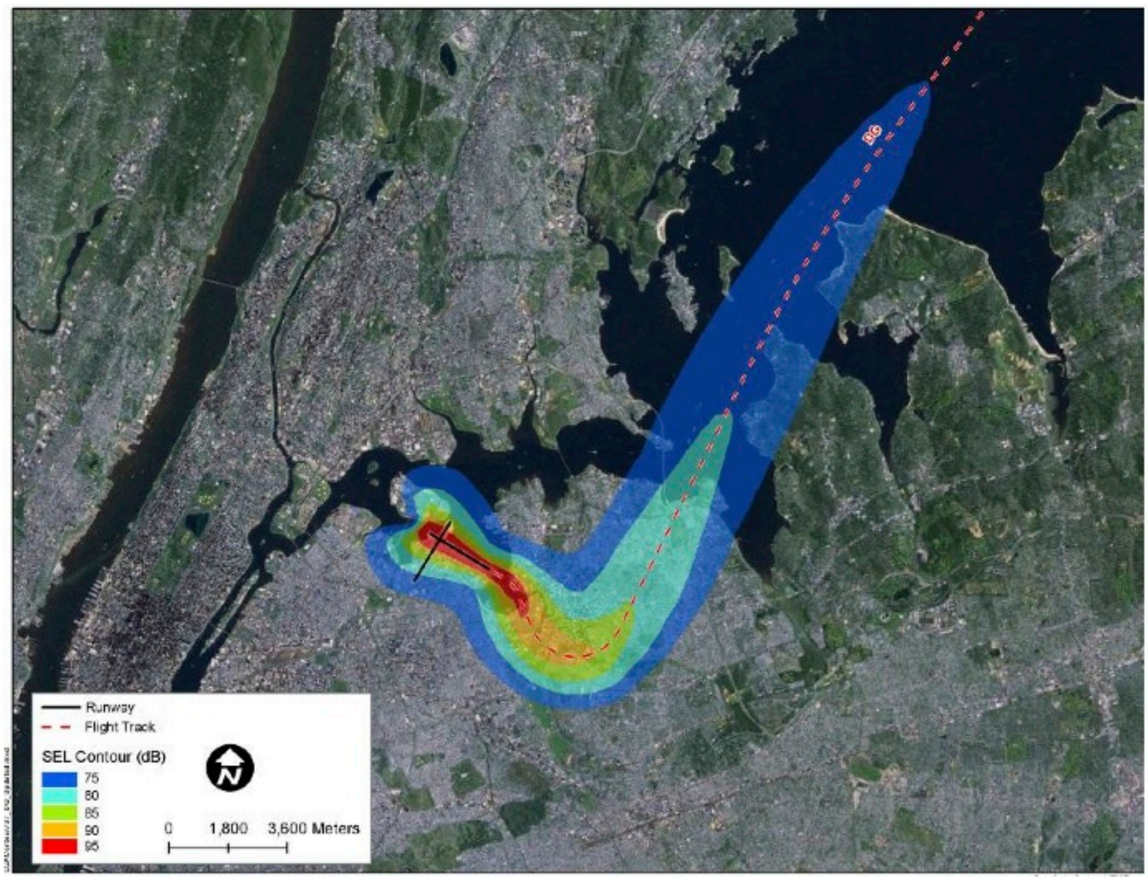

Figure 16: Noise Footprint for Today's Narrow-Body Engines at LaGuardia Airport[25]

With significantly lower noise levels, the same chart for the GTF, shown below, shows a substantial reduction in noise

[25] Source: Pratt & Whitney

levels. The 75 decibel area in blue now barely reaches the shoreline, and the 90 decibel area in yellow extends only a half mile from the edge of the airport.

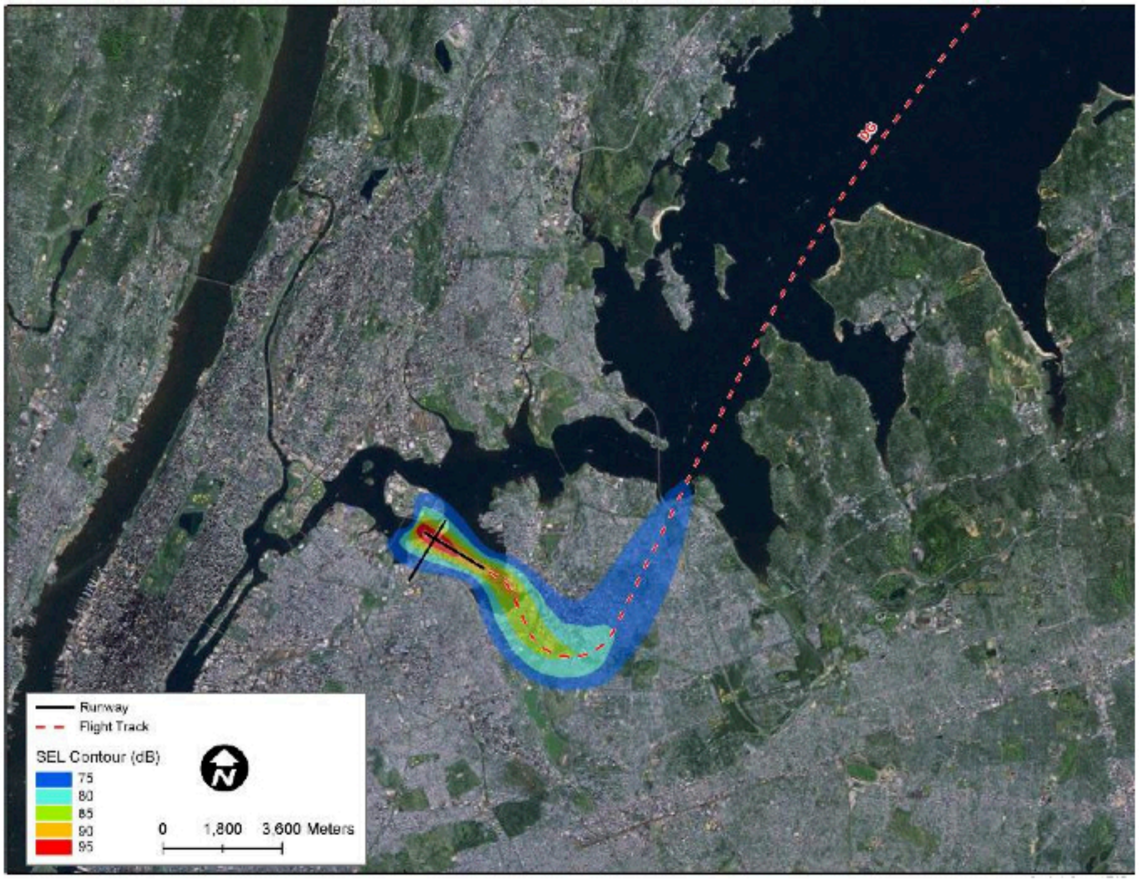

Figure 17: Noise Footprint for PW1000G at LaGuardia Airport[26]

This means that the aircraft with a PW1000G engine will be more welcome in noise sensitive communities, and for those airports that adjust landing fees on the basis of noise, such as Amsterdam Schipol , taxes and fees will be lower, decreasing airline operating costs.

The GTF is the first of a new generation of "green" aircraft engines, and will significantly exceed current standards for noise and emissions.

[26] Source: Pratt & Whitney

VI. Economics - A Dual Advantage Over the Competition

Designing an aircraft engine involves trade-offs. One can find a way to improve fuel burn, but that improvement might come at the cost of additional engine heat and higher maintenance costs. Alternatively, one might set a goal to minimize maintenance costs, but that might require a trade-off in key engine performance characteristics, or weight. Obtaining the right balance is the challenge engineers face daily as they develop new engine technology.

The geared architecture has enabled design engineers at PW to break away from what has been a traditional trade-off between performance and maintenance costs, gaining a competitive advantage in both. This is accomplished by using the propulsive efficiency of the slower turning fan in conjunction with a simpler core with fewer parts. Since the laws of physics remain constant, it is logical that fewer parts, all things being equal, would translate to lower maintenance cost.

The CFM International LEAP engine will enter service shortly after the GTF. These two new generation engines will offer similar improvements in fuel economy. However, unlike previous generations the manufacturers have diverged significantly in their use of technology, resulting in two distinctly different configurations. PW has chosen a geared turbofan configuration, while CFM has chosen a more conventional direct drive configuration with a two-stage high pressure turbine.

Both engines have multiple aircraft applications, offer lower fuel burn, lower emissions and lower noise levels than today's engines. Each of the new narrow body engines promises equal, if not better, maintenance costs than today's benchmark.

LEAP FROM CFM INTERNATIONAL

The LEAP engine is produced by CFM International, a joint venture of General Electric and Snecma, a unit of Safran in France. It is an all-new engine designed to replace the venerable CFM56 currently in use on the Boeing 737NG and Airbus A320 families. This engine incorporates technologies developed from CFM parent company GE, in particularly from the proven GE90 and recently developed GEnx wide-body engine programs.

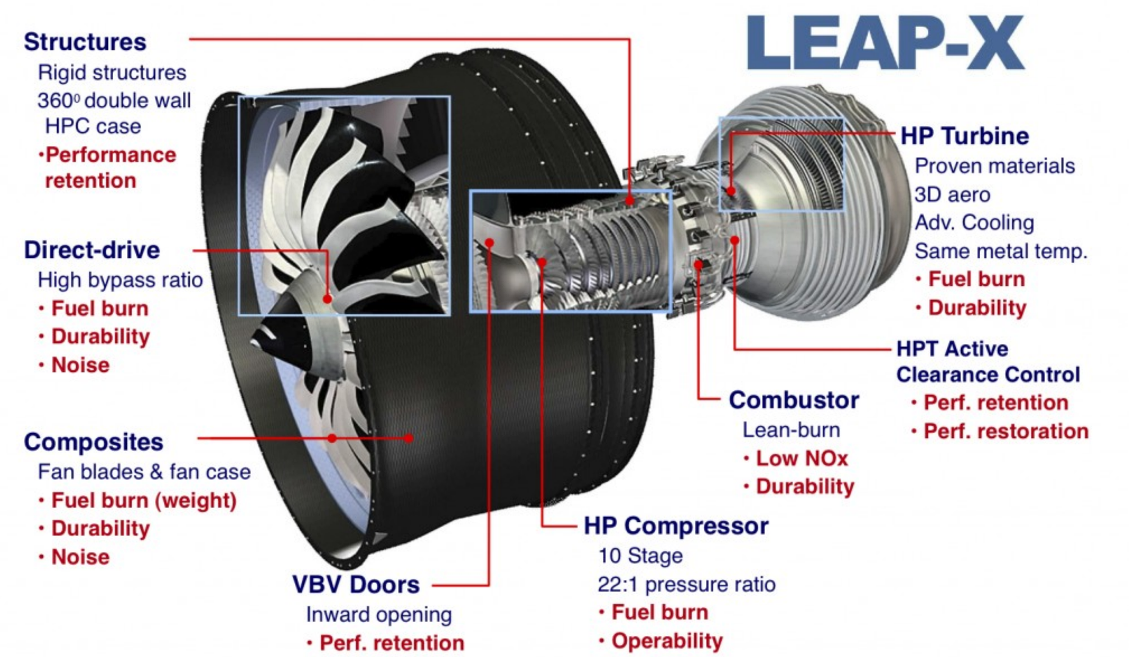

Figure 18: Key Features of LEAP engine[27]

Several advanced technologies have been applied to LEAP. One of the most notable is the 3-D woven 18-blade composite fan and composite fan case, which reduce weight, extend durability and by using more advanced aerodynamics, reduce both fuel burn and noise. The LEAP composite fan, built using a resin transfer molding ("RTM"), provides an 11:1 bypass ratio and is the first use of composite fan technology in the single-aisle engine market. CFM has the benefit of more than 26 million flight hours with composite blades gained on the GE90, but RTM

[27] Source CFM International

is an even more recent technology, wherein the blades are woven in three dimensions rather than built up with layers of composite plies.

The engine core also features anti-FOD (Foreign Object Damage) technology, which inward facing Variable Bleed Valve doors and a buried High Pressure Compressor inlet combine to create a virtual FOD free core.

The 10-stage High Pressure Compressor has a 22:1 pressure ratio, helping to minimize fuel burn. A new, lean-burn TAPS (Twin Annular Pre-Swirling) combustor will provide low NOx emissions and has been designed for durability.

The two-stage High Pressure Turbine ("HPT") section adds advanced coatings for cooling metal parts enabling the same metal temperatures as today's engines despite having a higher gas path temperature. The design of the HPT includes third-generation three-dimensional aerodynamics and active clearance controls to maintain high engine performance.

THE GTF FROM PRATT AND WHITNEY

The GTF engine features a fan drive gear system that allows the fan to operate at lower speeds than the low-pressure compressor and turbine. This increases the by-pass ratio and results in a significant improvement in fuel consumption, emissions and noise.

Using a geared configuration, the GTF is the first ultra-high bypass ratio turbofan, with a bypass ratio of 12.2:1. The engine features a light-weight titanium-aluminum alloy aerodynamically shaped fan, shrouded by a composite fan case. The efficiency of the fan, with lower operating speeds, provides a significant increase in propulsive efficiency and thereby fuel economy.

The gear, or fan-drive gear system, is at the heart of the new configuration for this geared turbofan design. PW has designed a durable reduction gear system, with no life limited parts, capable of handling the higher thrust of a commercial engine without a significant weight penalty.

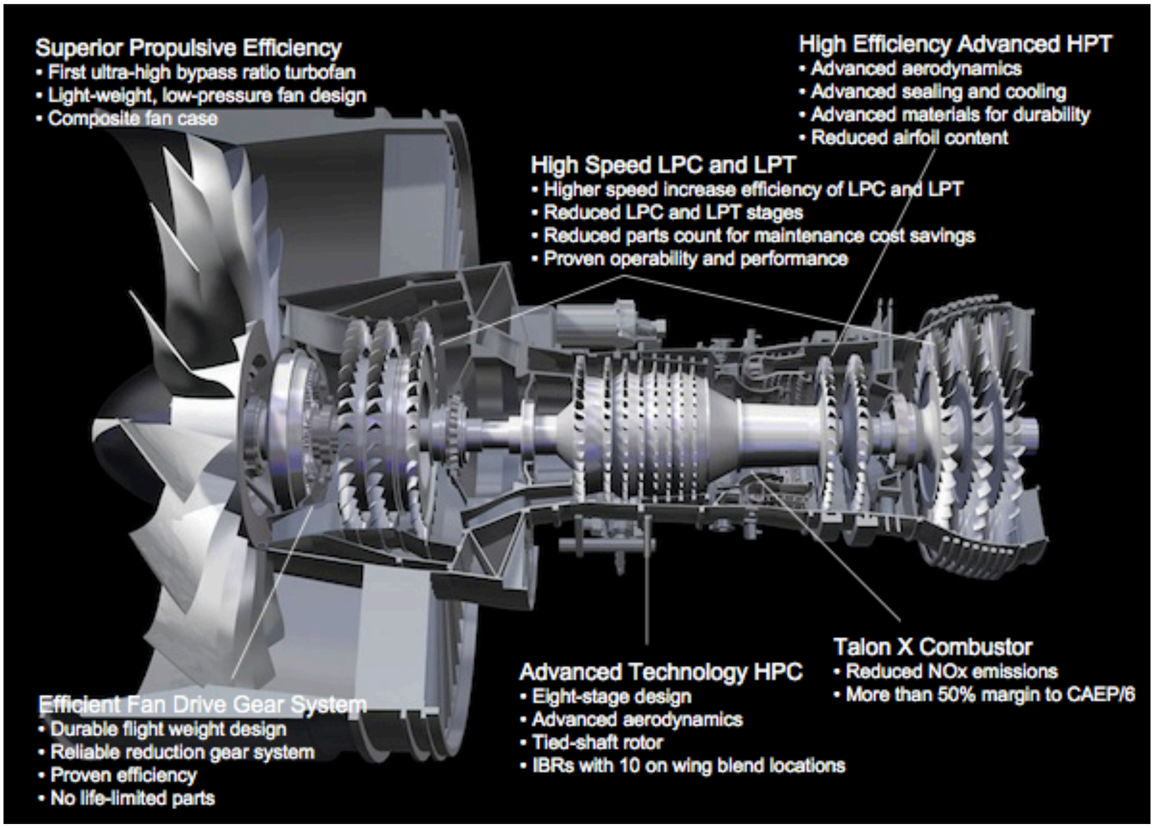

Figure 19: Key Features of the PW1000G Engine[28]

A new core also contributes to increased efficiency. The low-pressure compressor has been designed for high speed operations. That design reduces the number of stages required and results in a lower parts counts to minimize maintenance costs. The high-pressure compressor has an eight-stage design, with advanced aerodynamics and a tied-shaft rotor. It utilizes blisks (integrated-bladed rotors) with ten on-wing blend locations that facilitate easy maintenance.

The Talon-X combustor is a third-generation high-efficiency lean-burn combustor that reduces NOx emissions by 50% to ICAO CAEP/6[29] standards.

[28] Source: Pratt & Whitney

[29] Standards are developed at ICAO meetings of the Committee of Aviation Environmental Performance or CAEP. CAEP/8 standards are the most recent to be proposed by the committee which meets every two years.

The High Pressure Turbine is a two-stage design with advanced aerodynamics, advanced sealing and cooling, advanced materials for increased durability, and fewer airfoils than prior designs. The Low Pressure Turbine has been optimized for high speed operations, and has a reduced parts count for maintenance cost savings.

PERFORMANCE IMPROVEMENTS ARE SIGNIFICANT FOR BOTH ENGINES

The CFM LEAP will be the replacement for the CFM-56, and will be offered on the Airbus A320neo, Boeing 737MAX and the Chinese COMAC C919. The GTF will be offered on the A320neo family, replacing the IAE V2500, and has been chosen to power the Bombardier CSeries, Yakovlev Yak-242, Mitsubishi Regional Jet, and Embraer E2 Jets.

The manufacturers have each promised up to a 16% reduction in fuel burn for the new engines, which will be introduced in 2015 on the CSeries for the GTF and in 2016 on the A320neo for the LEAP. Each will offer an advanced combustor with 50% reduction in NOx emissions from CAEP/6 levels. Each will also be significantly quieter than today's engines, with a 15dB reduction on A320 neo, which means both engines will make less than half the noise produced by today's engines. PW and CFM each promise noise footprint reductions of 75%.

One area of difference, however, is maintenance cost. CFM is projecting equivalent maintenance cost to the CFM56-5B for the LEAP and PW is promising a significant reduction in maintenance costs over the life of the engine than current engines. PW's has targeted maintenance costs 20% lower than today's V2500 engine for the GTF series.

MAINTENANCE COSTS

With more than half of new engines under "power-by-the-hour" maintenance contracts, the reliability of an engine will directly impact the profitability of the program.[30] As the by the hour payment from the airline is fixed, any improvements in engine reliability will fall directly to the bottom line of the engine manufacturer.

[30] Dramatic changes in the engine aftermarket are causing major concerns for aircraft investors, Airfinance Journal, 12 March 2014

Comparing each element of the new technology engines with each other, along with the existing benchmark, the CFM56-5B, provides an indication of how maintenance costs will likely evolve. US DOT Form 41 data indicates that the CFM56-5B has lower maintenance costs than the competing IAE V2500. The V2500, however, burns less fuel.[31] Airlines evaluate the trade-offs between fuel burn and maintenance cost in making their engine selection between the CFM-56 and V2500 today, and a similar decision will be required as GTF and LEAP, also two excellent engines, enter the market.

ENGINE CONFIGURATIONS

The GTF uses a geared turbofan configuration, adding a gearbox enables the fan to turn slower than the remainder of the engine, which will rotate at a higher speed to optimize performance. The CFM LEAP utilizes a more conventional direct drive configuration.

The engine configuration impacts the number of stages required in the compressors and turbines required to achieve the projected performance. The following table compares the number of stages in each engine section for the PW1100G and CFM LEAP used on the Airbus A320neo, and compares them to the existing CFM56-5B used on the Airbus A320.

ENGINE STAGES	LEAP	PW1000G	CFM-56-5B
Fan	1	1	1
Gearbox	none	1	none
LP Compressor	3	3	3
HP Compressor	10	8	9
HP Turbine	2	2	1
LP Turbine	7	3	4

Figure 20: Comparative Number of Engine Stages for LEAP, PW 1000G and CFM-56-5B Engines

[31] United States Department of Transportation collects financial performance data from airlines, continuing Form 41 that was used by the Civil Aeronautics Board. That data is collected quarterly and publicly available for analysis.

Both new engines will utilize a two-stage High Pressure Turbine rather than a single stage HPT, as used on the CFM56. By adding a gearbox, PW is able to reduce the number of engine stages while achieving its fuel burn goal, while LEAP adds stages to achieve its fuel burn goal. The LEAP, when compared with the CFM56, adds stages in the HPC, HPT and LPT sections to achieve its performance improvements. The GTF, by adding a gearbox, has fewer sections than CFM56 in the HPC and LPT to achieve its performance improvements, instead relying on higher rotational speeds made possible by the geared configuration.

COMPARING THE LEAP AND GTF FROM A MAINTENANCE PERSPECTIVE

Based on each manufacturer's claim, the LEAP is projected to have equal maintenance costs with the CFM56, and the GTF cost could be significantly lower than today's engines. With fewer parts, one would expect the GTF to be lower in maintenance costs than the CFM LEAP.

Such a comparison is best accomplished by looking at the engine from front to back on a section-by-section basis. A diagram comparing the engine configurations is shown below.

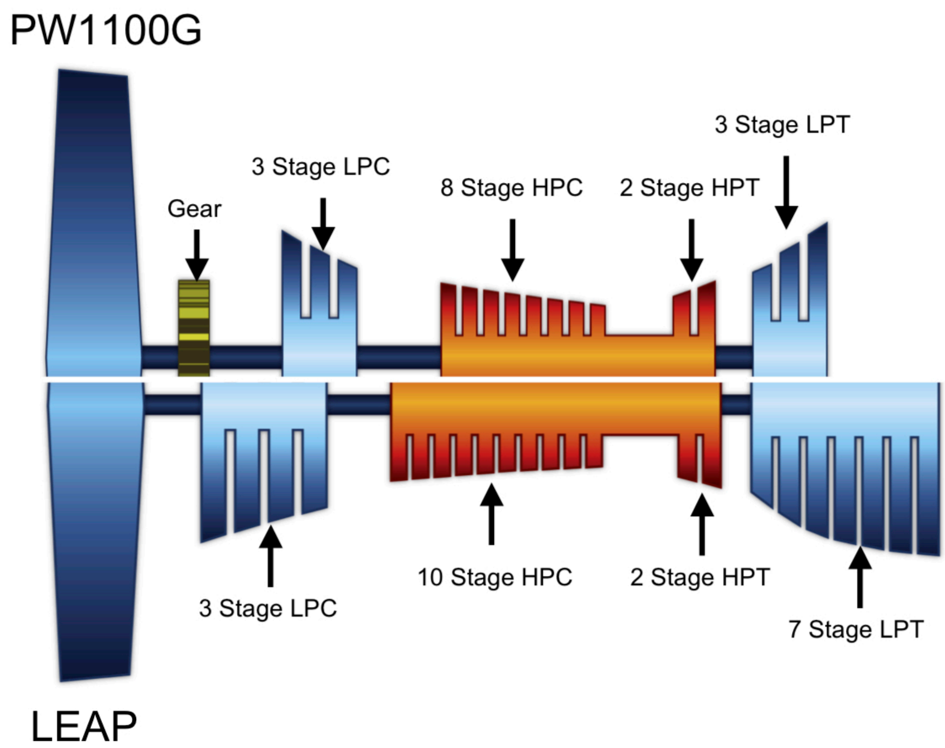

Figure 21: Engine Stage Comparison, PW1000G vs. CFM LEAP[32]

AirInsight estimates that the GTF will have between 1,500-2,500 fewer airfoils, six fewer stages, and approximately the same number of life limited parts in its configuration than the LEAP.

GE has indicated that its count of airfoil difference is in the 1,500 range, based on their comparative estimates, but was unable to provide us with projected airfoil counts for the LEAP, citing the proprietary nature of an engine still in design. PW similarly would not provide detailed airfoil counts, but indicated that the difference could be significantly higher than GE's estimate.

At this point, the designs are well established in the development process, and the information we've gleaned indicates a significant difference between the two engines in airfoil counts.

While the manufacturers are keeping their blade counts as proprietary information, there are clearly fewer airfoils in

[32] Source: Pratt & Whitney

the PW GTF than in the LEAP. As parts count is a driver of maintenance cost, the key question then becomes how will wear affect the parts in each engine..

The GE-designed core for the LEAP features coating technology that will enable parts to not only withstand a 200 degree increase in engine path temperatures while keeping metal temperatures constant, but also improve their wear performance. PW features fewer parts with higher rotation speeds to optimize engine performance that will also utilize advanced technologies to improve wear performance.

We may need to wait until engines are in service to determine how well both engines meet their goals, as with increased temperatures, and in the case of the GTF, higher rotational speed, wear patterns may be different than today's components.[33] But both companies are betting their futures, as well as their "by the flight hour" maintenance contracts, on their new technologies.

So far, in initial test engines, wear has been lower than projected for the GTF, a positive sign that their technologies will be successful. LEAP, which is scheduled for later entry into service, has reached the stage of full engine testing, with positive reports on performance. Ultimately, the key to maintenance success will be how well the new materials, coatings, and cooling processes work in high cycle environments.

Traditionally, the core of an aircraft engine accounts for over 90% of maintenance costs, with this highest concentration in high-pressure sections. AirInsight doesn't foresee a break from this trend in either new engine, particularly since both will utilize two-stage rather than single stage high-pressure turbines to generate thermal efficiency.

Our comparison begins at the front of the engine, working rearward.

Fan Section: The LEAP has an 18 blade composite fan, compared with a 24 blade metallic fan for the CFM56-7B and 36 blade metallic fan on the CFM56-5B. The GTF will utilize an 18 blade bi-metallic fan. Each will have a larger

[33] Steven Udvar-Hazy, CEO of Air Lease Corp., told the 2012 ISTAT conference in Barcelona that the two engines will have to be in service six to eight years before the industry truly understands the promises/performances made by PW and CFM.

fan than the CFM56, with a 78” fan for LEAP and 81” fan for PW1000G on the A320neo.

Comparing the two approaches, composite materials will be slightly more expensive than the bi-metallic blades, but will also be lighter, and potentially more durable.

LEAP also incorporates foreign-object damage (FOD) reduction technology in its design, with a centrifugal design that ejects FOD through doors. PW’s design, using a translating sleeve, provides an alternative mechanism to block FOD, and cites their lower fan pressure ratio as a factor in not bringing in as much debris into the engine. Each of these technologies will help lower maintenance costs, as eliminating FOD reduces engine damage.

Each fan design should be more efficient than current engines, and we believe that maintenance costs for the fan section, typically about 5% of total engine maintenance, will be roughly equivalent between the new engines. *Advantage: DRAW*.

Gearbox: As LEAP has no gearbox, it clearly has an advantage in maintenance costs over the GTF. Maintenance cost of this gearbox is projected to be low, as the gearbox has only seven moving parts and a robust lubrication system to minimize wear. Even though the costs for gearbox inspections should not be as significant as some initially feared, due to PW’s innovative technology, gears do require periodic maintenance. We estimate the gearbox will require about 2-3% of total engine maintenance cost. *Advantage: LEAP.*

The majority of maintenance costs will come from the core:

Low Pressure Compressor: Both engines have a 3 stage LPC, but the GTF will have fewer airfoils, based on the preliminary design information we’ve been provided by both companies. However, the GTF will be rotating much faster. We would expect similar to marginally lower maintenance costs for GTF in this section given the difference in the number of airfoils, potentially offset by higher rotational speeds. *Advantage: DRAW*

High Pressure Compressor: The GTF has 8 stages versus 10 for LEAP and we estimate, about one-third fewer airfoils in this section. While the PW1000G will rotate slightly faster than LEAP, given the significant difference in airfoils, we project lower maintenance costs for GTF in this section, as these are both high speed compressors. *Advantage GTF.*

Combustor: Both engines utilize advanced combustor designs that have similar characteristics, including dual annular designs with RQL technology. While both will be more efficient than prior versions, they will each be more complex than today's technology, and will likely be more expensive to replace and maintain. Pratt & Whitney utilizes its third-generation Talon combustor while CFM uses GE's advanced technology TAPS combustor, introduced on their advanced wide-body engines. *Advantage: DRAW.*

High Pressure Turbine: In this engine section, with high operating temperatures, wear can be significant, and this part of the core can account for 60% of engine maintenance costs. The key question is how well the specialized coatings and materials used in the LEAP will protect the engine, which is expected to have gas path temperatures 150-200 degrees hotter than the CFM56[34]. If these coatings work well and improve the durability of the components, despite the higher temperatures, LEAP should be able to maintain reliability equivalent to, or even better than its current parts. But we expect such parts, adding coating and cooling technologies, will be more expensive than existing parts without such coatings.

Engine performance comes from a blend of propulsive efficiency (generated by the fan) and thermal efficiency generated by the core. Roughly 50% of a modern engine performance is dictated by each element. The GTF, with a larger, slower turning fan, has an advantage in propulsive efficiency, and the LEAP, to provide the equivalent fuel burn improvement, would need higher thermal efficiency. That would require a hotter burning engine.

At equivalent temperatures, we would expect about a net 2-3% differential in fuel burn between the engines, given the difference in bypass ratio and fan efficiency, and

[34] We have been provided data on operating temperatures and pressure ratios from both Airbus and Pratt & Whitney and have utilized that data in our analysis.

thereby conclude that to provide equivalent fuel burn performance, the LEAP will need to run at hotter temperatures and have higher pressure ratios than the GTF.

The GTF is expected to run about 70 degrees hotter than the CFM56, and PW believes it can maintain reliability while keeping metal temperatures equivalent with its design. While these gas path temperatures are 60-130 degrees lower than LEAP, these higher temperatures can still negatively impact wear, and will require cooling technologies.

In addition, the GTF will be rotating at much higher speed than the LEAP, which helps optimize performance, but the rotational dynamics could also adversely impact wear and tear on parts. PW cites a proprietary cooling technology to accommodate both higher temperatures and minimize the impacts of rotational dynamics to minimize wear, but PW won't describe those technologies, citing them as a trade secret.

Coatings and cooling mechanisms must work well to ensure durability in either engine. But in looking at a blend of temperatures, airfoils and rotation speed, we believe the high-pressure turbine maintenance costs will be substantially higher for both engines than the single-stage CFM56. PW has experience with a two stage HPT, as the V2500 has a proven two-stage design. With anticipated lower operating temperatures and fewer airfoils, we would expect an advantage for the GTF. *Advantage: GTF.*

Low Pressure Turbine: This engine section has a major difference, with 3 stages for the GTF and 7 stages for LEAP. In terms of parts, this translates to about two thirds fewer airfoils for GTF than LEAP, a significant difference. Even with higher rotational speeds, the GTF, with fewer parts, should achieve lower costs in this section than the LEAP. *Advantage GTF.*

Maintenance Cost Impacts

Our preliminary estimates indicate that the GTF should have a slight advantage in maintenance costs over LEAP. We would expect the PW1000G to be 2-5% lower in total maintenance cost than the LEAP, based on the stage-by stage-analysis above.

We understand from airlines that preliminary cost data from Airbus indicate a slight advantage for the GTF over the LEAP for application on an Airbus 320 in both fuel burn and engine maintenance costs. The fuel burn advantage ranged from 1%-2%, depending on model and distance flown. Routine maintenance costs were also projected with a similar slight advantage of 1%-2%, depending on the model, utilization pattern, and operational range.   The differential with respect to life limited parts was substantial, and a double-digit advantage for PW, likely reflective of the difference in the number of airfoils and complexity of some life limited parts.

The net result is that the GTF offers an engine choice that offers both better fuel burn and better maintenance cost than the competition. As a result, airlines are not forced to choose between a fuel burn and maintenance trade-offs.

Today, PW holds a slight market share advantage over LEAP on the A320 family, but 34% of the aircraft customers have yet to select and engine.

Of course, both engine manufacturers are excellent at pricing to the point of economic equivalence, and we expect that both commercial and technical concerns will determine engine selection in the marketplace.

The exclusivity for LEAP on Boeing products provides a commercial advantage for that engine for airlines ordering both Airbus and Boeing narrow-bodies, as a higher degree of commonality can be maintained with a single vendor.

VII. Future Growth and Development

The initial offering in the GTF line-up provides impressive advances -- 16% lower fuel burn, a 12:1 bypass ratio, and a 75% reduction in noise. But this is only the starting point for the new technology GTF engines. PW has a development plan to improve fuel burn, on average, by 1% per year over the next decade. Although the first engines have not yet entered service, R&D efforts on a second generation GTF engine are well underway.

Technological improvements to the existing GTF will begin with a likely increase in the gear ratio from the current 3:1 ratio to a ratio of 4:1 or 4.5:1. This will enable additional optimization of fan speeds, and provide an even higher bypass ratio, likely in the range of 15:1 to 18:1 as the engine evolves over the next decade.

Ambitious Targets

With a target averaging 1% per year over the next decade, by 2025, PW should have engine models that are 26% more fuel efficient than today's models using the same architecture as the GTF.

That efficiency will be improved in two ways. First, propulsive efficiency will be increased through a larger gear ratio and even slower turning fan. This will enable more by-pass air to flow around the engine core, saving fuel, reducing noise, and reducing emissions in the process.

The core will be further optimized, and tailored for the higher rotational speeds from the new gear ratio. The core will achieve a higher overall pressure ratio, and likely have higher operating temperatures, requiring PW to introduce additional cooling technology. We expect pressure ratios to move from about 50 for today's engines to 60 or even 70 within a decade.

Competitive Comparison

Having fewer engine stages provides a competitive advantage for PW over their CFM, as PW has the capability to add additional stages to its engine for performance growth. The LEAP, with six more stages in its engine, has little room to add additional stages without negatively impacting the length of the engine, presenting ground clearance issues.

While both the PW GTF and CFM LEAP provide significant fuel economy, emissions, and noise improvements over today's engines, the major difference appears to be in the potential for continued improvement. PW has a roadmap for continued improvement on their new architecture. CFM appears to be reaching the limits on what can be achieved with a conventional architecture.

Scalability

The GTF is the first truly scalable engine, and may actually improve the larger it becomes. Designed initially for smaller thrust applications, the engine can be expanded upwards quite easily through scaling the size of components. With the tightest tolerances designed for small thrust applications, upward expansion of the engine provides substantial flexibility, as tight tolerances will not be an issue. We could easily see an application in the 40,000 pound thrust range for a Boeing 757 replacement, or even a wide-body variant in the 75,000-100,000 pound thrust class as new aircraft applications merit consideration.

The Future

Strong opportunities for growth differentiate the GTF from its competitors. Over the next decade, the GTF will provide growth in performance that its competitor will be hard pressed to match, as well as growth through the scalability of the engine to thrust levels appropriate for new narrow-body and wide-body applications.

The flexibility, and growth potential, of the GTF engine was one of the key factors for Bombardier, Airbus, Mitsubishi, Yakovlev, and Embraer in selecting the GTF for their next generation of aircraft.

VIII. Conclusions

Pratt & Whitney has developed a breakthrough that enables them to leapfrog their competition for narrow-body engines. The geared architecture enables slightly better fuel burn and environmental performance than their competitor using a simpler core with fewer parts, providing lower maintenance costs.

With a path for future performance growth that is expected to reach 1% per year over the next decade, the GTF is well positioned to further exploit the geared technology. CFM, with its LEAP engine, appears to be pushing the limits of technology in a conventional configuration, and will be hard pressed to keep up with that pace of growth.

As a result, we expect the geared configuration to become a standard within the industry. Already Rolls Royce has joined PW with their plans for a new geared engine. We expect that CFM and GE will not be far behind.

First movers travel down the learning curve faster than followers, and PW has a first mover advantage in applying geared technology to engines for commercial aircraft. That advantage does change everything for Pratt & Whitney, and what's possible for its airline customers and the environment.

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