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CLIFF GARRETT TURBOMACHINERY ENGINEERING AWARD

2013-01-2228

HTF7000 Engine Design, Development and Uses

David K. Winstanley
Honeywell International

Presented at:
SAE 2013 AeroTech Congress & Exhibition
Montreal, Canada
September 25, 2013

CLIFF GARRETT TURBOMACHINERY ENGINEERING AWARD

Description

This award promotes engineering developments and the presentation of SAE papers on turbomachinery and/or developments that enable or advance the use of turbomachinery. The award honors Cliff Garrett and the inspiration he provided to engineers by his example, support, encouragement, and many contributions as an aerospace pioneer. To perpetuate recognition of Mr. Garrett's achievements and dedication as an aerospace pioneer, SAE administers an annual lecture by a distinguished authority in the engineering of turbomachinery and/or engineering related to creating, enabling, or advancing applications of turbomachinery in power systems, on-highway, off-highway, aircraft, and/or spacecraft uses.

The Award

This award, established in 1984, is administered by the Garrett Award Selection Committee and consists of a framed certificate, a commemorative gift and an honorarium. The award is made possible by a contribution from the Garrett Corporation (now a division of Honeywell).

The lecture honors the memory of Cliff Garrett, an Aircraft pioneer and entrepreneur. Under Cliff's leadership, Garrett was the first to build small auxiliary power gas turbines. One APU series that Cliff's engineers started in the 1950's is still in production today. This is the 85 series, a product that has outlived the company that bore Cliff's name.

Although Garrett ceased to exist as a corporation in late 1987, individual Garrett divisions thrived under the AlliedSignal Aerospace banner until its acquisition by Honeywell. These divisions include the Phoenix-based Garrett Auxiliary Power Division and the Garrett Engine Division, which produce APUs and propulsion engines respectively.

Cliff had an overriding determination to see his company established as a propulsion engine supplier. This was just beginning to happen when he died in 1963. Cliff's successor made that goal a reality. Cliff had an intensity and drive that were unequaled. He built Garrett from ground zero to a billion dollar company. Growth from within was achieved by product engineering innovation, as well as by a strong and dedicated sales team. Cliff represented a personalized, hands-on leadership style that was just right for his time and his company. We will always need leaders of his spirit and vision.

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CLIFF GARRETT TURBOMACHINERY ENGINEERING AWARD

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David K. Winstanley
Honeywell Aerospace

David K. Winstanley is currently the Director of Mechanical Chief Engineers for Honeywell Aerospace. Mr. Winstanley is responsible for managing all Chief Engineers who provide design approval and safety review for all Honeywell mechanical products. Mr. Winstanley has previously been responsible as Senior Chief Engineer for developing and installing integrated mechanical systems for the Airbus A350 extended mechanical systems perimeter (EMSP) and JSF/F35 power and thermal management system (PTMS).

Mr. Winstanley was also, as Chief Engineer for Commercial Propulsion Engines, responsible for the design, development, certification and fielding of the HTF7000 turbofan engine.

Mr. Winstanley received BSME & MSME degrees from Purdue University. Mr. Winstanley is a proud member of SAE International.

2013-01-2228
Published 09/17/2013
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doi:10.4271/2013-01-2228
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HTF7000 Engine Design, Development and Uses

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ABSTRACT

Honeywell has developed a unique turbofan engine for application to the super mid-size business aviation market, the HTF7000. This paper will describe the design of this engine including aeromechanical design of its components. The unique design features of this engine will be described along with the technology growth path to keep the engine current. This paper will also describe several features which have been developed for this engine in response to new regulatory requirements. Some aspects of the engine to aircraft integration will also be described.

CITATION: Winstanley, D., "HTF7000 Engine Design, Development and Uses," *SAE Int. J. Aerosp.* 6(2):2013, doi: 10.4271/2013-01-2228.

ENGINE FAMILY

The HTF7000 engine is the commercial name for a family of engine specifically designed for the super-mid-sized business jet. The HTF 7000 powers the Bombardier Challenger C300; the HTF7250 powers the Gulfstream G280; and the HTF7500 is proposed to power the Embraer Legacy 450. These engines installed on their respective aircraft are shown in Figure 1.

The HTF7000 family is certified with the FAA designation of AS907 and produces maximum takeoff thrust in the range of 6500 to 7800 lbf. The engine certified ratings are presented in Table 1. The HTF7500 is thermodynamically larger than the other two engines, but the specifics of the flat ranging scheme lead to the specific certification ratings in the table.

Table 1. HTF7000 Engine Family Type Design Comparison (Sea Level Static (SLS) Uninstalled Conditions)

Engine Rating or Limit	HTF7000 (AS907-1-1A) (Certified)	HTF7250 (AS907-2-1G) (Certified)	HTF7500 (AS907-3-1E) (Proposed)
Thrust, MCT (lbf)	7,050	7,337	7,335
Thrust, MTO (lbf)	7,050	7,765	7,638
Low spool speed, MCT (rpm)	9,739	9,800	9,800
Low spool speed, MTO (rpm)	9,830	9,830	9,830
High spool speed, MCT (rpm)	27,530	27,530	27,530
High spool speed, MTO (rpm)	27,686	27,686	27,686
Inter-turbine Temperature, MCT, °F(°C)	1,729 (943)	1,742 (950)	1,742 (950)
Inter-turbine Temperature, MTO, °F(°C)	1,735 (946)	1,751 (955)	1,751 (955)

ENGINE OVERVIEW

The HTF7000 is a 4.2 BPR, two-spool, co-rotating turbofan engine featuring a simple design (see Figure 2). It derives its thrust from a single-stage, wide-chord, damperless, high efficiency, inserted-blade fan rotor that is driven directly by an uncooled three-stage low pressure turbine (LPT). The engine compressor core consists of four axial compressor "blisks" (i.e., integrally bladed disks) with two stages of variable and three stages of non-variable axial vanes; and a single-stage centrifugal compressor. The axial and centrifugal compressor rotors are driven by a two-stage, cooled high-pressure (HP) turbine (HPT). The HP and LP spools rotate in the same direction.

The entire rotating system is supported by a bearing and seal system containing only two sump areas, both of which are located in cool environments (i.e., no sump under the combustor). The combustor is a through-flow, annular, effusion-cooled configuration. To reduce noise and improve efficiency, a forced mixer is used to merge the fan bypass and core flows together prior to their exiting the engine through a converging-diverging nozzle embedded in the thrust reverser. The engine includes the full-authority digital electronic control (FADEC) system, which features dual channel electronic control in the form of two independent electronic control units (ECUs); the customer bleed system, providing two sources of bleed air sources to the aircraft; and the accessory gearbox (AGB), which is designed to accommodate airframe needs for such accessories as the generator and hydraulic pump.

The design approach for the HTF7000 engines incorporated two major objectives: (1) to maintain turbine temperatures at a level that precludes the use of exotic materials and thereby keeps maintenance and acquisition costs low, and (2) to provide thrust growth capacity for potential future needs. The selected BPR of 4.2 strikes a balance between engine weight, diameter, noise, and specific fuel consumption (SFC). The moderate core pressure ratio of 16:1 allows the use of economical, lower-pressure customer bleed air during cruise, which improves installed performance.

Figure 1. HTF7000 Turbofan Engine Installed on Super Mid-Size Business Aircraft

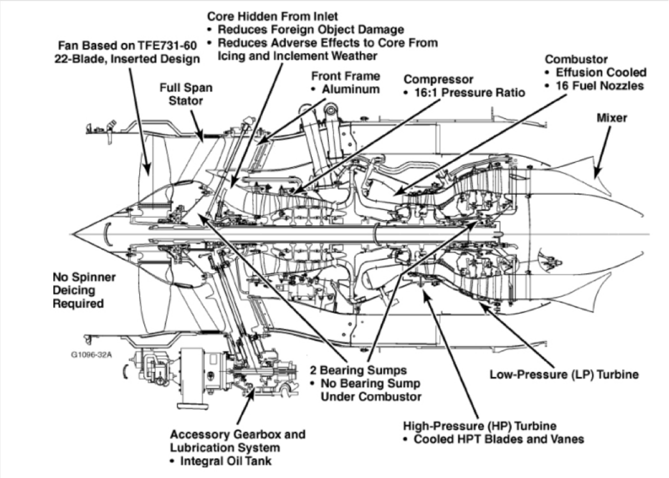

Figure 2. Key Features of the HTF7000 Turbofan Engine

Fan

The HTF7000 fan is comprised of three major subassemblies: the fan rotor and stator (single fan stage), the fan inlet housing, and the structural front frame. Figure 3 presents some of the key features of the fan design.

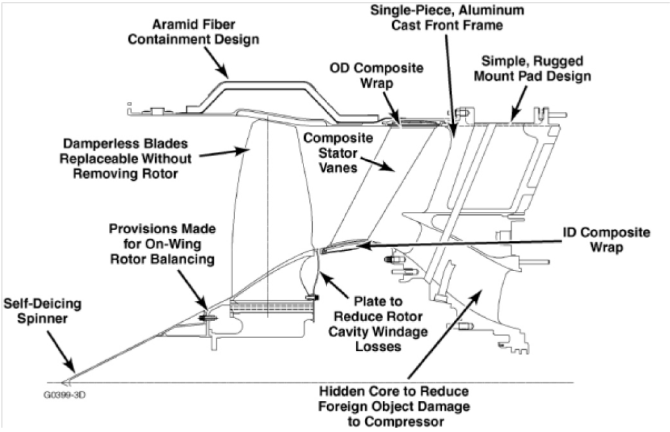

Figure 3. Key Features of the HTF7000 Fan

The fan rotor contains 22 titanium, damperless, wide-chord, inserted blades, combining robust design, high performance, light weight, and low cost-of-ownership features. The fan blade attachment and titanium disk design incorporates proven features of Honeywell's certified TFE731-60 engine and a bolted rotor configuration for improved maintainability. The fan blades are easily removable on wing rapid turn around and repair. The fan rotor combines a low hub-to-tip radius ratio with high specific flow to provide high engine thrust with minimal frontal-area for reduced installed drag and reduced exposure to environmental icing. The fan spinner is a robust, aluminum, two-piece design with a conical shape. Its geometry is based on the CFE738/TFE731 design that has been proven to operate without the need for an anti-icing system. The fan stator is a full-span composite assembly mounted in aluminum hub and shroud rings with elastomeric grommets. The inlet housing is an aluminum/aramid fiber design, based on the proven CFE738-1 design, providing light weight, blade containment, and rotor tip abradable capability. The front frame is a single-piece aluminum casting with eight struts in the core and bypass, based on proven designs from the CFE738-1, TFE731-20/-40/-60, and ALF502/LF507 engines.

The wide-chord, damperless fan technology developed by Honeywell for the TFE731-60 engine was adapted to the HTF7000 design, providing a low-risk development approach. The high fan pressure ratio was developed with ample stall margin by using a low-aspect-ratio blade design proven to operate at high Mach numbers with high levels of efficiency. The high hub pressure ratio provides additional boost to the compressor for improved performance and increased cabin bleed pressures. The added temperature rise inherent in this design reduces the probability of ice formation. Additionally, the high pressure rise at the fan hub reduces the magnitude of inlet distortion transmitted to the core compressor, resulting in improved compression system stability.

The HTF7000 fan blade containment system uses an aluminum honeycomb material surrounded by a simple aramid fiber wrap for the optimum balance of light weight and containment capability. This configuration is used in the CFE738 engine. The structural front frame uses cast aluminum technology similar to that used in Honeywell's TFE731-20/-40/-60, CFE738, and ALF502/LF507 engines. The position of the front frame flow-path splitter relative to the rotor trailing edge is prescribed by trajectory analysis predictions for objects (birds, ice, inclement weather, etc.) ingested by the fan. The result is a well-hidden core flow-path inlet, reducing the potential for foreign object damage (FOD) to the core, and eliminating the need for any anti-icing system for the engine.

The HTF7000 fan mechanical support incorporates a frangible support in the No.1 bearing region. The frangible support is designed to maintain structural support and stiffness during normal operation and during a 1½- or 4-pound bird ingestion event, and to preclude excessive loads from being transmitted into the front frame structure during a fan blade-out event. Once a predetermined radial load is reached, the frangible link shears, permitting the fan to seek a new center of rotation without transmitting the full loads from the event into the surrounding structure, inlet, or engine mounts. Fan motion is limited, radially and axially, by the bearing support structure. The frangible support effects better control over the maximum load during a severe load event, thereby achieving better structural integrity.

The unheated conical spinner is based on the TFE731 and CFE738 turbofan engines. Over 7,200 Honeywell engines are in service with unheated conical spinners, having accumulated over 35 million cumulative hours of operation. No reported engine damage due to ice ingestion and no known anomalies regarding engine operation in icing conditions have been recorded for Honeywell engines configured with unheated conical spinners.

The fan blades were designed to maintain sufficient frequency margin on all critical resonances and to ensure blade strength and reliability relative to bird impact requirements.

Compressor

The HTF7000 high-pressure compressor consists of three major subassemblies: a four-stage axial compressor, a single stage centrifugal compressor, and supporting structure. The HTF7000 compressor design built on a successful advanced technology development and validation effort (known colloquially as the AS900TVT) in which the baseline designs and technologies were demonstrated in a core engine. Both the A900TVT and the HTF7000 compressor design emphasized robustness and low parts count for improved reliability and cost of ownership. Key features and attributes of the compressor are shown in Figure 4.

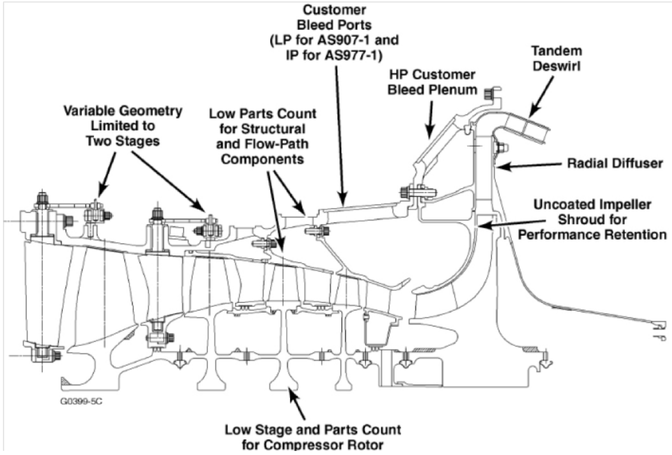

Figure 4. Key Features of the HTF7000 Compressor.

The compressor rotor assembly includes four blisk rotors, the associated spacers, and the impeller, primarily connected via curvic couplings. The blisks and impeller airfoils are "flank milled" for improved producibility. The axial compressor stationary components consist of five vane rows and the compressor cases. The first two vane rows, the inlet guide vane (IGV), and the first stage stator are variable to permit the engine control system to maintain good compressor performance and operability margin at part speed conditions. The compressor variable geometry (CVG) is located in a manner that shields the components from adverse environmental conditions and is designed for long life. The other vane rows are integrally cast in 360-degree rings. The axial compressor stages have abradable blade track coating to accommodate blade tip incursions and maintain good compressor performance. To maximize compressor efficiency and stabilize the operating range, each of the four axial compressor stators has an inner-band abradable seal to accommodate the rotating labyrinth seal knives in restricting reverse-flow leakage. The axial and centrifugal compressors are mounted on the common HP spool shaft. The impeller discharge flow passes through a radial diffuser, a 120-degree flow-path bend, and a tandem deswirl vane assembly that directs the low-velocity, high-pressure airflow to the combustor.

Materials selected for the HTF7000 compressor rotors are forged titanium for light weight and corrosion resistance. The IGV and first stage stator are fabricated from forged stainless steel, and the later stage axial stators are fabricated from cast nickel-base material. The IGV inner and outer, and the first stage inner, vane supports are fabricated from aluminum. The compressor case and shroud system incorporates the widely used titanium and nickel-base materials; titanium is used only over the first stage rotor, while nickel-based material is used over the remaining axial stages and the impeller. Abradable coatings are applied to the axial compressor shrouds to ensure optimum blade-tip running clearances and component reparability.

A close-coupled aero-mechanical optimization system used for the compressor design ensured an optimum solution. The HTF7000 design has lower loadings, which translate into higher surge margin when compared with similar Honeywell designs. Three-dimensional single-blade-row and multistage viscous analyses were used to determine the operability characteristics of the compressor. In addition, flutter analysis was conducted on the rotor airfoils, verifying that the design is free of flutter. The compressor is designed in a manner that hides its inlet from most of the particles entrained in the fan discharge flow stream, minimizing exposure of the engine core to FOD, ice, and inclement weather. The diffusion system consists of a radial diffuser and a tandem deswirl that together deliver flow to the combustor with almost no residual swirl and at low Mach numbers.

Combustor

The HTF7000 combustor consists of a combustion chamber (combustor), fuel nozzles, igniters, and a plenum. The combustor is effusion cooled to provide low metal temperatures for long life. Significant effort was focused on low cost and producibility, with the resulting features incorporated into the combustor design, such as machined swirler assemblies, simplified fuel nozzles, and rapid laser effusion drilling.

The HTF7000 combustor is sized to attain minimum cold-side pressure loss in the flow annulus, thus using the majority of available pressure loss across the combustor for mixing fuel and air and for controlling pattern factor. Combustor airflow distribution is optimized for efficient combustion, low pattern factor, altitude light-off, and emissions using Honeywell's 3-D computational fluid dynamic (CFD) combustor performance flow model, which has been validated on various prior combustor designs. The combustor flow-path design and the fuel nozzle and swirler combination were designed to uniformly mix the fuel and air. This uniform mixing eliminates circumferential hot streaks, while preventing fuel impingement on the combustor walls and any potential carbon formation.

To achieve long time combustor lives, two major features were incorporated into the HTF7000 design. One of these is effusion cooling with thermal barrier coating (TBC), selected for temperature control. Effusion cooling is used for all new combustor designs at Honeywell, and is currently used on the TFE731-20/-40/-60 engines, the CTS800 engine, the RE220 and 331-500 auxiliary power units (APUs), and the LT101 propulsion engine. The other major feature for achieving the life goal is the use of Haynes 230 material.

The HTF7000 fuel injection design optimizes spray quality for ignition and uniform flow matching at all operating conditions through the combination of 12 pure airblast fuel nozzles and 4 dual-circuit start nozzles. The system was based on technology available from the TFE1042 engine, and successfully demonstrated successful and reliable starting to an altitude above 30,000 feet. The HTF7000 combustor is designed for robust lean stability, with sufficient margin to avoid the pressure fluctuations encountered when a combustor is operated too near lean blowout.

The HTF7000 engine incorporates an ecology and flow divider valve in the fuel supply to the fuel nozzles. During engine shutdown, the ecology and flow divider valve piston pulls the fuel from the fuel nozzles and holds it until the next start, thereby preventing the fuel nozzle coking that would normally occur during engine shutdown and soakback. This approach was chosen also to provide environmental value by preventing the fuel remaining downstream of the control valves from evaporating into the atmosphere as was common in older engines.

As described in reference [1], smaller engines (< 9,000lbs thrust class), and especially those designed for business jet applications have a more difficult problem statement in achieving emissions requirements. The HTF7000 was initially certified to all relevant emissions requirements at the time of certification; however, recognizing that these requirements were changing in the near future and that engine and aircraft needed to demonstrated their environmentally friendly designs, Honeywell embarked on a technology development program to improve combustor emissions specifically minimizing and balancing nitrous oxides, unburned hydrocarbons, carbon monoxide, and smoke.

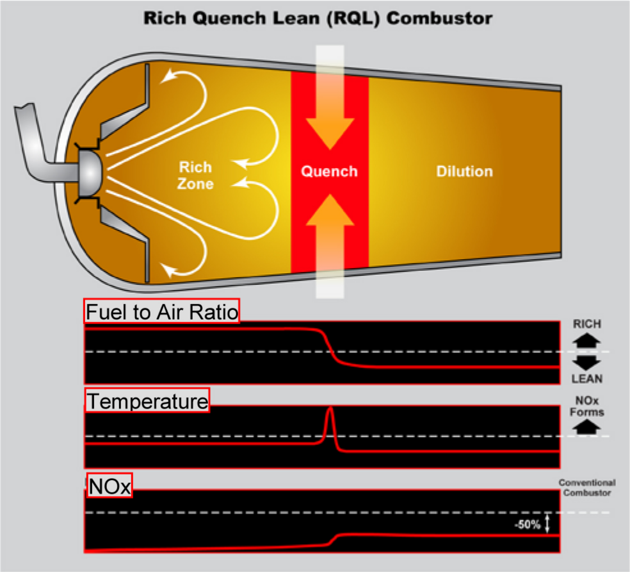

Figure 5. The Rich-Quench-Lean Combustor

Honeywell's approach to achieving these goals is called Single Annular comBustor for Emissions Reduction (SABER). SABER is tiered technology program designed to deliver improved combustion emissions over time while the engine grows. SABER has successfully employed the Rich-Quench-Lean (RQL) concept (illustrated in Figure 5). The first tier (SABER-1) was completed and certified for incorporation into the HTF7000 engine in 2010. The SABER-1 measured NOx emissions to be better than 27% margin to the ICAO CAEP/6 requirements, and has met all other operability and durability requirements for certification.

The key design features of this first tier SABER combustor are illustrated in Figure 6. The second tier SABER is well under way and expected shortly; in addition, Honeywell is applying this technology to its auxiliary power units (APU) to reduce their emissions as well.

The initially certified HTF7000 combustor design made extensive use of computational fluid dynamics (CFD), but validated those results with combustor rig testing. The SABER combustor design has substantially benefitted from advances in modern CFD with the result being reduced testing required. An example of the results of this CFD for the SABER combustor is presented in Figure 7.

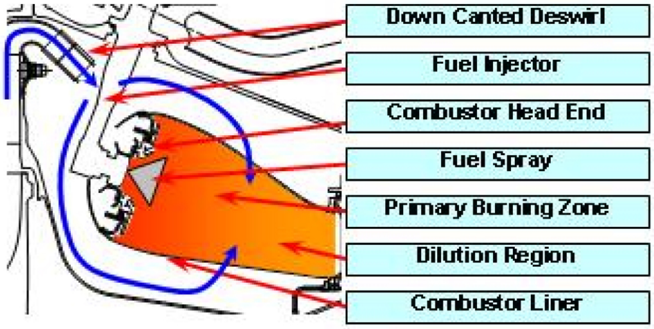

Figure 6. SABER-1 Geometry & Changes to Achieve Emission Targets

High Pressure Turbine

The HTF7000 high pressure turbine (HPT) is a two stage turbine as shown in Figure 8. All four airfoils are actively and efficiently cooled. The disks are mated with seal plates that allow cooling air to be delivered and provide positive axial retention of the blades. A tangential on-board injector (TOBI) system is used to efficiently deliver high pressure air to the first stage blade. The first stage and second stage HP stators are cast and segmented. The blade tip shroud segments are coated with TBC material on the gas-path side to reduce shroud temperatures and tolerate light blade rubs.

Materials selected for the HTF7000 HP turbine include Honeywell's proprietary single-crystal material for the first stage blade, directionally solidified standard material for the second stage HP blade, specially processed Inconel 718 for the rotor disks, and seal plates. Knife seals on the first stage seal plate and second stage HP seal-plate coupler are hard-coated for improved rub tolerance.

The turbine stators are cast equiaxed MAR-M 247 coated with diffused platinum aluminide. This material combination has been successful on the TFE731-4/-5 and TFE731-20/-40/-60 series engines. The cooling effectiveness designed for the HTF7000 ensures that vane and blade metal temperatures are lower than targeted for similar material combinations in the TFE731 engines. The blade tip shroud segments are made of IN738LC and HA-230, respectively, materials chosen for high-temperature creep strength and oxidation resistance. The tip shroud support structure is made of Waspaloy, which provides the strength necessary for blade containment.

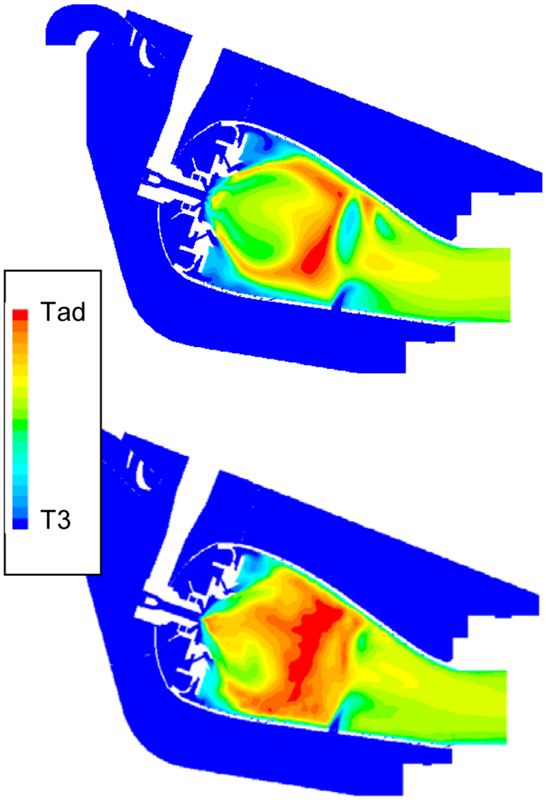

Figure 7. CFD predicted Temperature Contours at the Fuel Injector Centerline comparing RANS and time-averaged LES simulations

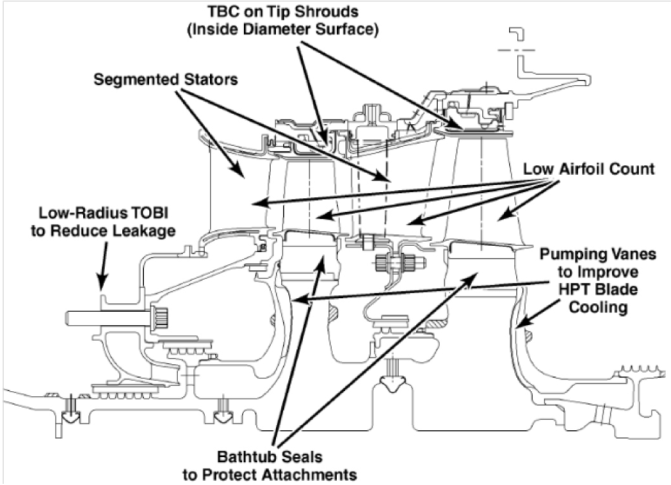

Figure 8. Key Features of the High Pressure Turbine

Cooling schemes used in the HTF7000 HP turbine module are those that are being successfully used on existing Honeywell production engines. Platform "bathtub" seals are used in both stages to minimize hot-gas ingestion into the attachment area, as well as to provide a vibration damping effect for the airfoil. The cooled stators for the HTF7000 incorporate design and manufacturing concepts successfully proven on the TFE1042 and TFE731-60 engines. The stators are cast as segments to enable individual replacement. Impingement tubes fit in a core cavity of the airfoil allow for effective cooling.

Low Pressure Turbine

The low pressure turbine is a three-stage rotor coupled directly to the fan, designed for minimal parts count and increased reliability. All blade stages have tip shrouds that provide vibration damping and tolerate light rubs without loss of performance. The turbine case configuration provides blade containment and is modeled after the proven CFE738 configuration. The exit guide vane reduces losses as the hot gases leave the engine core, and also provides routing for services required by the aft sump. There are no oil or scavenge services located between the HP turbine and the LP turbine; instead, they are supplied through the cooler exit guide vane. Key features of the HTF7000 LP turbine are shown in Figure 9.

The aft mount provisions consist of clevises that are part of the exit guide vane casting. There are four clevises arranged for side mounting, two for the right-hand installation and two (located on the opposite side) for the left-hand installation. The entire LP turbine can be removed or installed as a module. There are 17 borescope inspection ports in the turbine case for inspection of all three stages and the trailing edges of the second stage HP blade. The entire LP turbine module can remain in place while the aft HP and LP bearings and seals are removed or installed.

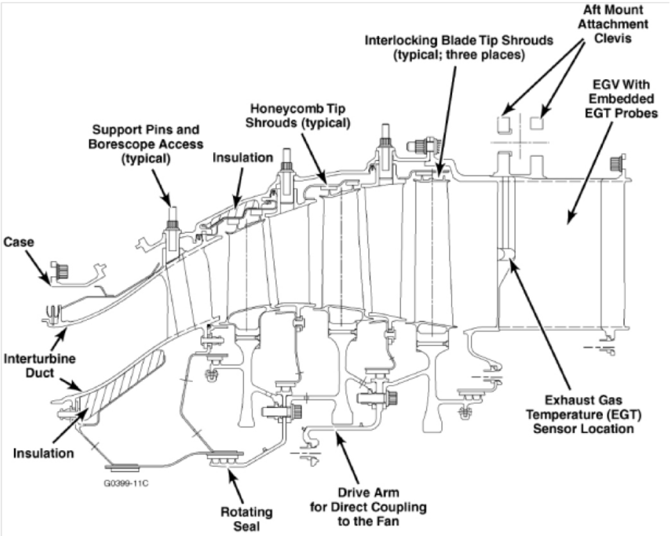

Figure 9. Key Features of the Low Pressure Turbine

The material used in the LP turbine case affects overall engine cost, weight, and performance. The case functions as the primary containment structure for the turbine, and controls blade-tip clearances for the first stage. IN718 was chosen as the case material for its containment capabilities, though turbine case temperature was also a key factor in the material selection. Experience and low density dictated the choice of IN100 for the HTF7000 LP turbine blades. The LP turbine disks are made of DP718. The disk forgings are fabricated using a “rolled ring” process, which yields properties equal to or better than the standard “closed die” process. This rolled ring process is used for flanges on the TFE731 engines and for containment rings on APUs. The drive arm and rotating seal are fabricated from DP718 forgings using the standard closed-die process. The stators are cast, full-ring components fabricated from MAR-M 247 (LPT1) and IN713LC (LPT2 and LPT3). The high strength and castability of IN718 make it the best choice for the EGV.

The altitude cruise condition was selected as the aerodynamic design point for the HTF7000 LP turbine. The engine specific-work requirement was met by designing a three-stage, moderately loaded turbine, and by selecting a turbine mean radius that would provide stage mean-work coefficients well within Honeywell's range of experience. The higher mean radius allows the turbine to operate at a higher efficiency, and reduces the risk associated with a close-coupled, lower radius turbine. The turbine flow path incorporates a long-chord EGV that results in a low airfoil count.

Secondary Flow System

The HTF7000 secondary flow circuit is designed to ensure proper cooling and purging of the turbine and sump cavities. The system uses air from three sources-the combustor plenum and Stages 3 and 4 axial compressor discharge to cool the HP and LP turbines.

The secondary flow system is designed to preclude the passage of foreign matter of unacceptable quantity or size. The core inlet configuration is designed to prevent the ingestion of large particles into the core by centrifugally separating these particles into the fan duct. Ingestion of small dust and foreign matter is allowed due to the robust design of the secondary flow system. All orifices, including impingement and film cooling holes in the high pressure turbine blades, vanes, and insert tubes, are sized sufficiently large to preclude blockage by small foreign matter. Also, additional “dust holes” are designed into the high pressure turbine blade tips to prevent accumulation of dust in the cooling passages. This “particle vent” concept has been successfully used on serpentine blade designs in Honeywell's TFE1042, AGT1500, and ATF3-6 engines. The effectiveness of these features for the HTF7000 secondary flow system was evaluated during engine endurance testing conducted in haboob conditions at Honeywell's San Tan desert test facility.

The HP turbine is cooled using a combination of air from axial compressor discharge and compressor exit. Compressor exit air actively cools the first and second stage HP turbine vanes. For the first stage vanes, the air is fed through both the OD and ID walls of the vane; for the second stage HP vane, the air is fed through metering pins in the OD of the vane. A small quantity of the air entering the impingement tube of the second stage HP vane is fed through the vane's inner end wall to purge the HPT interstage cavity. The HPT tip shrouds are impingement cooled via holes in the shroud support using air from the compressor exit.

Cooling air for the first stage blade is fed through the inlet inducer, which provides a preswirl for the air entering the rotating feed cavity for the blade. The second stage HP blade is cooled using air from the axial stage exit routed through the compressor shafting. This cooling air then passes between the HPT rotors and the HP shaft to the aft end of the HP turbine. The first stage and second stage HP seal plates have pumping vanes to maximize pressure rise to the second stage HP blade.

The HPT disks and seal plates are cooled primarily by the blade cooling air, which passes radially outward between the disks and seal plates. Additionally, the disks are cooled by cavity purge air in the interstage seal cavity. This interstage cavity purge air is supplied through the second stage HP vane and is discharged into the first stage disk aft rim cavity. This aft rim cavity air is metered by machined orifices in the second stage HP vane feed system. After passing into the first stage rotor aft cavity, airflow is metered across the interstage knife seal, then purges and cools the forward side of the second stage HP disk. The cavity on the aft side of the second stage HP seal plate is purged by LPT cooling air, which is metered through holes in the LPT panel seal.

The low pressure turbine is cooled using air supplied from axial stage exit which is routed externally to the LPT case. An internal baffle mounted on the first stage LPT vane assembly reduces heat transfer between the LPT cooling air and the hot surface of the duct outer flow path. After exiting the LPT case plenum, the LPT cooling air passes through the first stage LPT vane into an annular plenum that feeds cavity purge air to the aft face of the second stage HP seal plate and to the LPT1 rotor. An insulation blanket installed on the ID of the first stage LPT nozzle assembly flow path reduces heat absorption by the LPT cooling air in this annulus.

Accessory Gearbox and Lubrication System

The self-contained, integral HTF7000 engine lubrication system is based on other Honeywell production designs. Its performance has been enhanced by using the engine FADEC system to monitor oil pressures and temperatures, control the chip detector debris-clearing function, and perform diagnostics through the engine condition and fault reporting system. The lubrication system is designed to lubricate and cool the bearings, oil seals, splines, and gears. A fine-media oil filter is incorporated to increase bearing and gear lives. Effective scavenging and venting of the bearing sumps prevents oil churning and flooding of the bearings and seals. Air vented from the sumps is routed to the AGB, then through a serpentine-type air/oil separator, and finally into the nacelle drain mast. The accessory gearbox (AGB) takes advantage of TFE731 and CFE738 accessory gearbox technology by using an oil tank integral with the accessory gearbox, thus keeping the number of external lines to a minimum. The accessory pads incorporate non-contacting, lift-off face seals. A seal drain system is incorporated to capture any oil leakage and route it to the engine nacelle drain system. The AGB is removable on wing without removing the front frame or towershaft. The towershaft drive system transmits power from the engine HP spool to the AGB through the 6 o'clock strut of the engine front frame. The towershaft spline engagements are oil lubricated.

The oil supply system is an unregulated system with a simple, externally adjustable pressure adjusting valve. Oil is taken from the tank by a positive-displacement pump driven off the HP spool through the AGB, and passed through the oil filter and into the fuel heater/oil cooler before being supplied to the engine. A distribution network delivers oil to the various components via a series of metering orifices and jets. The system takes advantage of internally cored passages wherever possible to minimize the number of external pipes and fittings. Once the components have been lubricated and cooled, the oil is scavenged out by dedicated pump elements. This scavenge oil is directed through a full-flow, electronic chip detector to identify distress within the engine or AGB. The chip detector indication is transmitted via the FADEC to the aircraft maintenance systems. The chip detector incorporates a debris-clearing function to prevent nuisance indications. Engine maintenance action is further isolated toward individual sumps via magnetic plugs (i.e., debris monitors) installed in the respective sump scavenge passages.

The pumping elements for both the supply and scavenge oil circuits are based on gerotor configurations. Oil supply is provided by two main elements, whereas a total of six scavenge elements transfer oil back to the tank. A relief valve is incorporated in the oil filter module to limit elevated cold-start pressures. The oil pump drive-shaft bearings and splines are positively lubricated by cooled, filtered oil.

The primary filter in the lubrication system is located in the pressure pump discharge line. An aluminum filter bowl houses both the element and the pressure differential indicator. An impending filter bypass signal is transmitted via the ECU. A bypass valve is incorporated to maintain oil flow to downstream components in the event the filter clogs, and to prevent contaminants from reentering the system. During bypass mode, the system still provides a minimum filtration level by means of an accessible last chance screen. Externally accessible scavenge screens are also incorporated for added system protection. The oil supply is routed through the fuel heater - oil cooler, which is located upstream of the fuel filter to provide effective fuel heating and preclude the need for a separate fuel heater.

The HTF7000 AGB has pad and gear arrangements to meet the specific customer requirements for aircraft accessories (i.e., generator and hydraulic pump), speeds, rotations, and interfaces. The air/oil separator is common to all configurations, as are most of the bearings and seals. The items driven by both AGB configurations include the hydromechanical unit, permanent magnet alternator, cartridge oil pump, aircraft generator, and aircraft hydraulic pump. The

AGB incorporates quick-attach/detach connectors at the two customer accessory pads for ease of removing and installing the aircraft generator and hydraulic pump. The AGB is mounted to the engine frame in a manner similar to the CFE738 AGB, with the addition of a redundant mount to protect against the loss of a mount due to fire and a stabilizing strut to reduce AGB vibration in extreme icing conditions. Lubrication of the AGB is accomplished by a combination of oil jets for the critical bearings and gears, and splash lubrication for the other components. Baffles are installed around certain gears to minimize oil aeration and improve oil scavenging. Sealing is accomplished using noncontacting, lift-off carbon face seals. The towershaft system is designed to transmit a static torque that is higher than the actual maximum starting torque of the air turbine starter, plus the normal running loads with all accessories simultaneously loaded. The towershaft system incorporates the conventional spiral bevel gear scheme at the compressor shaft and AGB input shaft.

Shafting and Bearings

The HTF7000 rotor dynamic system is based on the TFE731, CFE738, and TFE1042 turbofan engines. The LP shaft system is supported by two roller bearings (Nos. 2 and 5) and a thrust bearing (No. 1). The hard-mounted No. 2 bearing in the LP rotor system positions the flexure critical mode above operating speed to minimize vibration and to avoid non-synchronous excitation. The HP turbine rotor system is supported by the No. 3 ball bearing at the forward end and by the No. 4 inter-shaft-mounted roller bearing at the aft end. The No. 1 and No. 5 bearings in the LP rotor system and the No. 3 bearing in the HP rotor system have squeeze film dampers that isolate the rotors from the support housings. The squeeze film dampers are optimized to provide softness and damping for the rigid body modes below idle speed.

There are three bearings in the engine forward sump. The No. 1 ball bearing supports the forward end of the LP fan shaft and provides axial thrust control. The No. 2 roller bearing supports the forward radial load of the LP shaft. The No. 3 ball bearing supports the forward end of the HP rotor and the thrust load of the HP shaft. The bearing design values do not exceed the bearing design experience of the CFE738 and TFE1042 production engines.

The HTF7000 main-shaft seal designs are based on successful CFE738, LF507, and TFE1042 engine designs. All of the main shaft seals are buffered using interstage compressor air to maintain a positive pressure differential under all engine operating conditions. Also, scavenging of the bearing compartment is configured to preclude oil buildup and prevent flooding at all attitudes within the flight envelope. The carbon ring-to-shaft clearance is minimized at high power levels, thereby limiting air leakage into the sump.

There are two cylindrical roller bearings in the engine aft sump. The No. 5 bearing supports the aft end of the LP shaft and the No. 4 bearing supports the aft end of the HP shaft. The No. 4 bearing is an inter-shaft bearing, configured so that the inner ring mounts on the HP shaft and the outer ring fits into a spring cage attached to the LP shaft.

Buffering air for the seals is extracted from the interstage compressor area and fed into the cavities outside the main-shaft seals to provide positive pressure differential across the oil seals and thereby prevent oil leakage. Buffering air is introduced to the forward sump seals via individual core passages inside the front frame. This buffering air purges the LP and HP shaft annulus to prevent oil leakage and coking. For the aft sump, No. 4 and No. 5 seals, a separate buffering air line is provide externally. A feature of the HTF7000 buffering system is the implementation of the double-drain labyrinth system for the forward sump seals. This system is located upstream of the aircraft cabin bleed ports, where any oil leakage could result in bleed air contamination. The double-drain system consists of a multiple series of labyrinth seals with a buffer air source supplied between the outer labyrinth knives. Two oil drains are provided, one on the inboard side located in the air cavity of the carbon seal, and the other on the outboard side located inside the buffering labyrinth seals. The drains purge any leaking oil into the respective cavities. The buffering system is also designed to prevent adverse pressure reversals across the seals during engine startup, motoring, and shutdown.

Reference [2] provides insight into an interesting development issue with the HTF7000 engine - non-synchronous vibration of the rotor system. As illustrated in Figure 10 (from reference [2]), the engine experienced high levels of vibration which did not correlate with any rotor speed characteristic (i.e. non-synchronous) and occurred in the high power, high speed operation regime. The aerodynamic destabilizing force in the engine obviously exceeded the system damping resulting in a non-synchronous whirl in the engine. Other contributing factors were found to be the stiffness of inter-shaft bearing spring cage, LP and HP rotor balance, inter-shaft bearing element internal clearance, No. 5 bearing squeeze film type and clearance, and No. 5 bearing support stiffness. While non-synchronous vibration is a known phenomenon in the turbine engine industry, this was Honeywell's first significant experience in resolving it. The resolution took significant development effort and is illustrated in Figure 11. A specially designed centering spring was developed to support the No. 5 bearing. This design used a soft spring to enhance modal damping combined with anisotropic stiffness, with 2:1 stiffness split between vertical and horizontal direction to provide modal damping and suppress instability. The anisotropy was achieved by asymmetrically arranging 6 beams. A bumper was added to limit center spring deflection during maneuver and blade loss events. Further, the centering spring forms the bearing outer race to reduce internal clearance of the rollers and the centering spring has an offset in the vertical direction to center the bearing under ‘1g’ load.

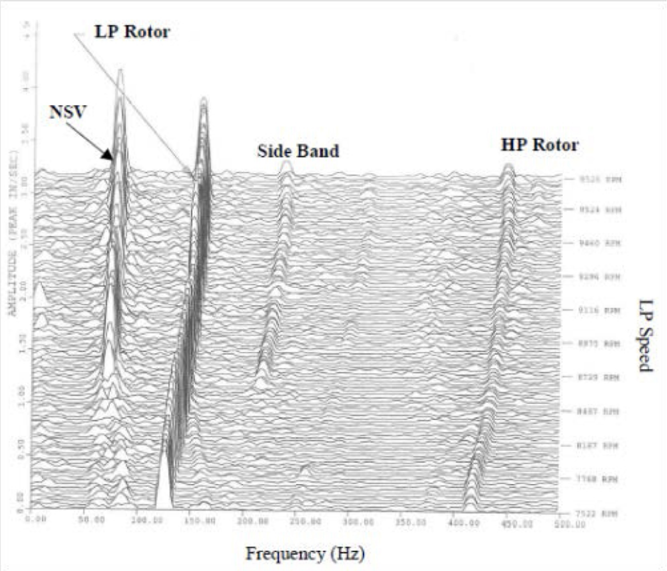

Figure 10. HTF7000 Non-synchronous Vibration Measurements (Reference [2]).

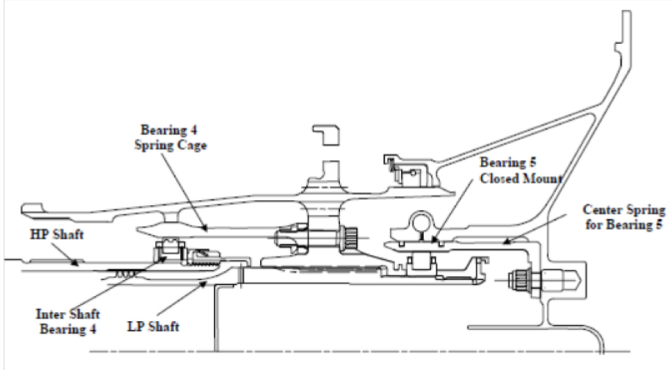

Figure 11. Centering spring support for No. 5 bearing designed to eliminate non-synchronous vibration

Ducting & Thrust Reverser

The purpose of the HTF7000 ducting and exhaust system is to control and direct engine airflow to produce thrust. The system comprises an inner bypass fan duct, an outer bypass fan duct, a mixer, a centerbody, and thrust nozzle incorporated into the stowed thrust reverser. An exploded view of the ducting, along with other nacelle components, and the thrust reverser is shown in Figure 12. The fan ducts direct the bypass fan airstream around the engine core, and then the mixer and centerbody mix the core and bypass airstreams. The design of the forward outer and forward inner fan ducts, including airflow contours, external pass-throughs, and Zone 2 cooling scoops, is similar for all versions of the engine exhaust systems. Zone 1 is the area outboard of the outer fan duct and is the cold fire zone. Zone 2 is the area between the inner fan duct and the engine core, and is the hot fire zone.

The forward duct section is a single-piece aluminum case that attaches at its forward interface to the engine front fan frame. The forward duct section incorporates removable access panels for maintenance of the core-mounted compressor variable geometry actuator and surge bleed valves, and for borescope inspection. The forward duct section also incorporates fireproof bulkhead provisions in the 6 and 12 o'clock struts for engine and aircraft services. The aft duct section attaches to the forward outer fan duct section via a flanged interface. The aft duct section comprises a support structure and removable acoustic panels, the latter providing noise attenuation as well as access for engine maintenance and inspection. The aft duct section also incorporates provisions in the 6 o'clock strut for engine and aircraft services. The aft duct section serves as the interface attachment for either an airframe supplied thrust reverser or forward thrust nozzle, both designated as aircraft-certified components. The outer fan duct is the firewall between Zones 1 and 2. All duct materials are fireproof, as are the seals, where necessary. The seals protect against fluid and air leakage.

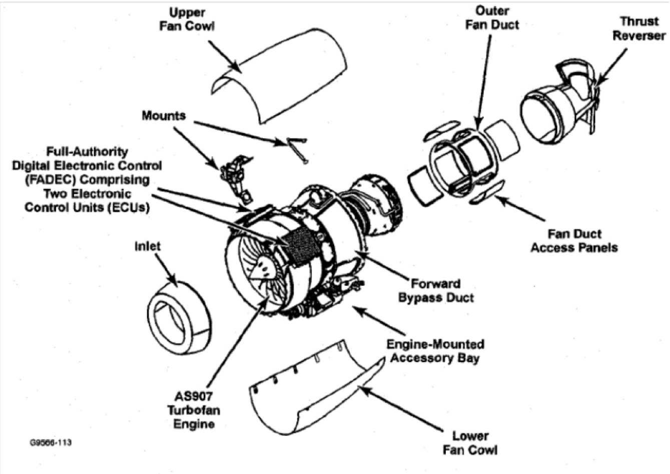

Figure 12. Exploded view of HTF7000 engine showing ducting, nacelle components, and thrust reverser.

The nacelle components (inlet, fan cowl doors, Part 25 engine build unit) plus the fan bypass ducting were designed, built, and tested by GKN Aerospace for the HTF7000. The thrust reverser was designed, built, and tested by Aircelle under contract to GKN and certified with the aircraft. The thrust reverser is illustrated in Figure 13. It is of some interest that Honeywell, GKN, and Aircelle completed sufficient analysis and testing that the thrust reverser to provide sufficient confidence such that the thrust reverser was deployed and used during landing on the first flight of the Challenger 300.

Control System

The engine is controlled by a dual-channel full authority digial electronic control (FADEC) system that is mounted on the engine (see Figure 12). There are two separately packaged

ECUs, in cast aluminum housings, plus associated sensors, actuators, and igniters, and the interconnecting wire harnesses. The FADEC system controls fuel flow, variable geometry, and surge bleed. The system also integrates powerplant monitoring and signal conditioning, and control or monitoring of other engine systems, including operation of the chip detector/zapper. Control of the thrust reverser is shared by the aircraft and the FADEC system, such that the powerplant alone cannot deploy the thrust reverser.

The FADEC system uses dual engine signals and dual actuation signals. There is a cross-channel data link between each channel on each engine, and two crossengine data links between the left channels of the two engines and the right channels of the two engines. Sensors are generally dual wound (separate inputs to each channel), and actuators are controlled by dual-coil torque motors. Certain sensors are single element with resistor and/or diode isolation. Each channel contains overspeed protection against control system overfueling failures. The overspeed protection circuits in each channel are independent of each other and the central processing unit, and each is capable of shutting off fuel in the event overspeed is detected. The FADEC system also includes a permanent magnet alternator which powers the control electrical and electronic components and system independent from the aircraft. A vibration sensor and monitoring system in FADEC conditions the signal to provide for cockpit annunciation and for ground-based fan trim balance.

Figure 13. Installed and deployed thrust reverser for HTF7000.

Certification & Flight Test

The certification test program comprised 22 engine tests, 20 rig tests, and 34 component tests, the former contributing to the total of over 19,000 hours of full-scale engine testing (development and certification) completed at the time of type certification.

In addition to the usual exciting tests (fan blade out, 4 lb bird ingestion), the HTF7000 was the first engine to complete multiple 1.5 lb bird ingestion testing with the (then) new run on requirements (roughly 75% thrust for 20mins with throttles moving). Similarly, the HTF 7000 successfully passed a severed shaft test - a first for Honeywell at the time.

As illustrated in Figure 14, Honeywell concluded that specialized flight testing was a preferred approach over altitude tank testing to achieve both development and certification altitude testing. A more detailed presentation of this flight test capability can be found in Reference [3].

Figure 14. Honeywell's flight test vehicles for certification and endurance flights:B720 with HTF7000 installed & B757 with HTF7500 installed [Photo Credit: Eugene Cupps]

SUMMARY/CONCLUSIONS

The HTF7000 engine has completed 10 years in service with more than 1.5 million hours of successful field operations. The HTF7000 has an in-flight shutdown rate of better than 1E-05 and a dispatch reliability of 99.9%, beating most industry benchmarks for business aviation aircraft engines.

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ACKNOWLEDGMENTS

The author wishes to acknowledge the hard work and long hours by literally hundreds of Honeywell (formerly Allied-Signal) employees who brought the HTF7000 from a clean sheet of paper to a highly efficient and productive engine. Without them, this paper, and the associated honor would not have been possible.

This paper is dedicated to Bonnie Critchfield without whose tireless, and accurate documentation methods, this engine would have never been certified, nor this paper written.

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