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T700 Engine Integral Inlet Separator

All Weather Operational Protection

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GENERAL ELECTRIC

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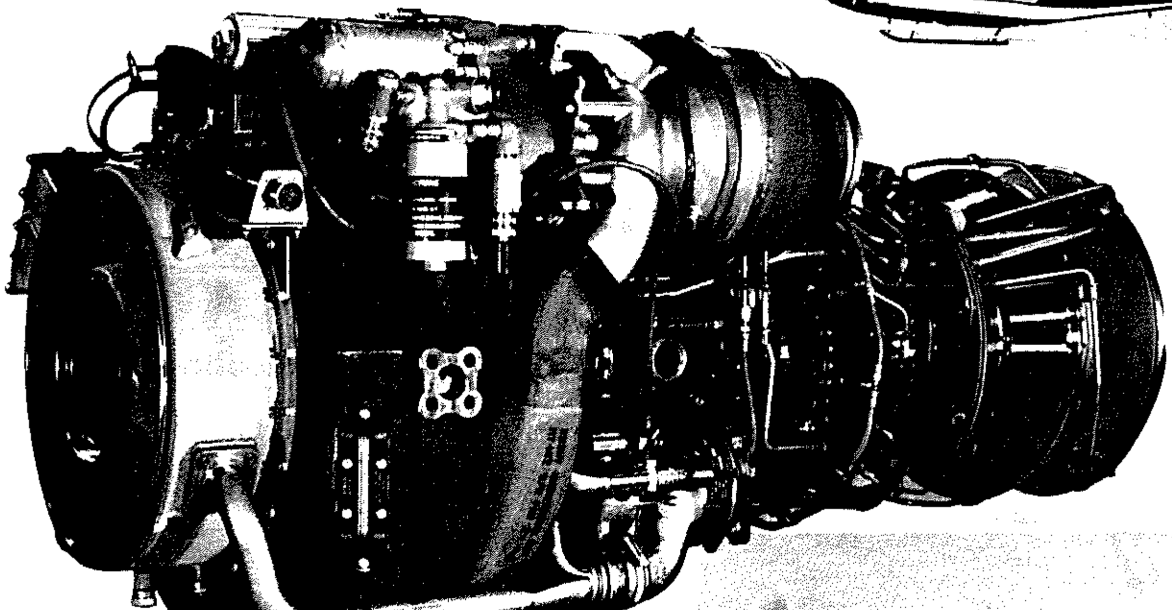
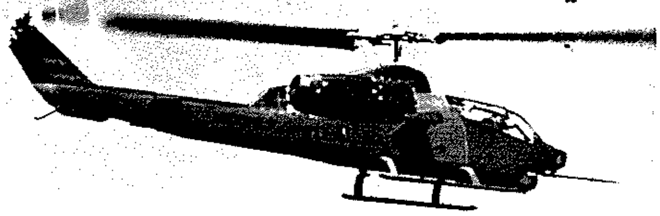
Bell 214ST

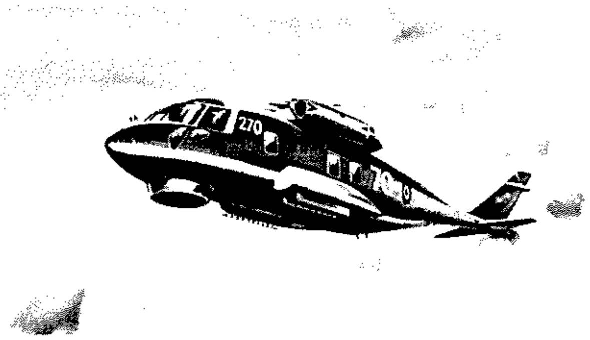


General Electric
T700 Turboshaft Engine

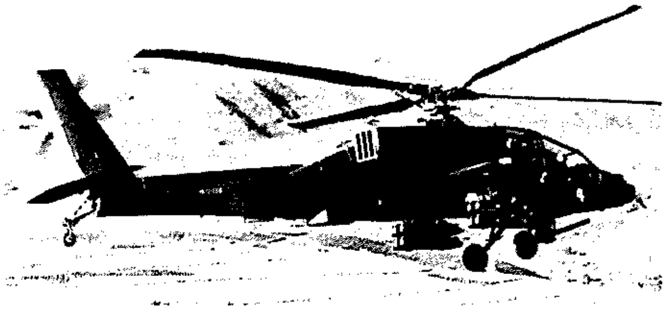


Bell AH-1T+

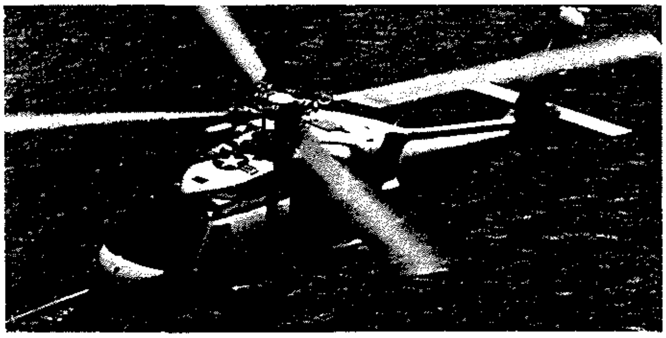
Sikorsky UH-60A Black Hawk



Westland WG.34A



Hughes AH-64 AAH



Sikorsky SH-60B LAMPS Mk III

Abstract

The General Electric Company's T700 turboshaft engine is an advanced design helicopter powerplant that combines a unique integral inlet particle separator with significant advances in performance, reliability and durability.

The T700 is now in production for the U.S. Army Black Hawk helicopter and has been selected to power the U.S. Army Advanced Attack Helicopter, the U.S. Navy LAMPS Mk III, the Bell 214ST and the Westland WG.34A. A prototype AH-1T+ is also being evaluated with twin T700 engines.

Although the U.S. Army had originally requested inlet separation to prevent internal engine erosion due to sand ingestion, experience has shown that inlet particle separation provides the core engine with superior protection from other environmentally caused damage.

Test results with birds and other foreign objects that cause compressor damage are, therefore, also presented in addition to a synopsis of test data highlighting sand separation efficiency.

GE turbine engine experience in northern Europe spans nearly three decades. During that time, the importance of protecting jet engines from ingestion of ice, snow and slush has been demonstrated repeatedly.

The T700 engine's ability to operate successfully under a wide range of climatic moisture conditions continues to build an increasing data base by combining engine qualification tests with aircraft field trials.

A summary of this T700 climatic experience includes the uniquely successful results of the Westland WG.34A/T700 inlet ingestion test program.

A brief description of other advanced integral inlet separator concepts suitable for the T700 and other turboshaft engines concludes this paper.

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T700 Inlet Separator Concept

Description

General

The General Electric Company T700 turboshaft engine has a unique inlet particle separator integrated into the forward main engine frames. The fully anti-iced separator provides a high level of compressor protection from sand and dust, birds, ice and foreign objects and other environmentally caused damage typical of helicopter operation.

The separator is designed to impart swirl to the entering airflow and extract that part of the flow containing the centrifuged sand and foreign material through a scavenge system energized by a mechanically driven blower (Figure 1). The clean air is then deswirled and enters the engine core.

The basic separator is formed by the swirl, the front and the main frames. The scavenge system is comprised of a fiberglass scroll cover and scavenge blower. These components are entirely integral with the engine.

Swirl Frame

The swirl frame is a stainless steel fabricated structure which incorporates the forward outer engine flange and front output drive pad. The flow path is formed by the cylindrical outer skin and an inner cone that provides line of sight protection for the compressor entry passage and also imparts radial direction to foreign objects. The frame has 12 constant chord, constant twist vanes that impart approximately 35° swirl to the air stream. The frame performs multiple functions. It is anti-iced by internal airflow, carries oil services to the front sump and is a structural member of the front mounting system.

Front Frame

The front frame is cast aluminum alloy. It provides a structural member for mounting loads and contains the output drive shaft assembly and accessory gearbox radial drive gear set. The flow path contains a cascade that deswirls the compressor

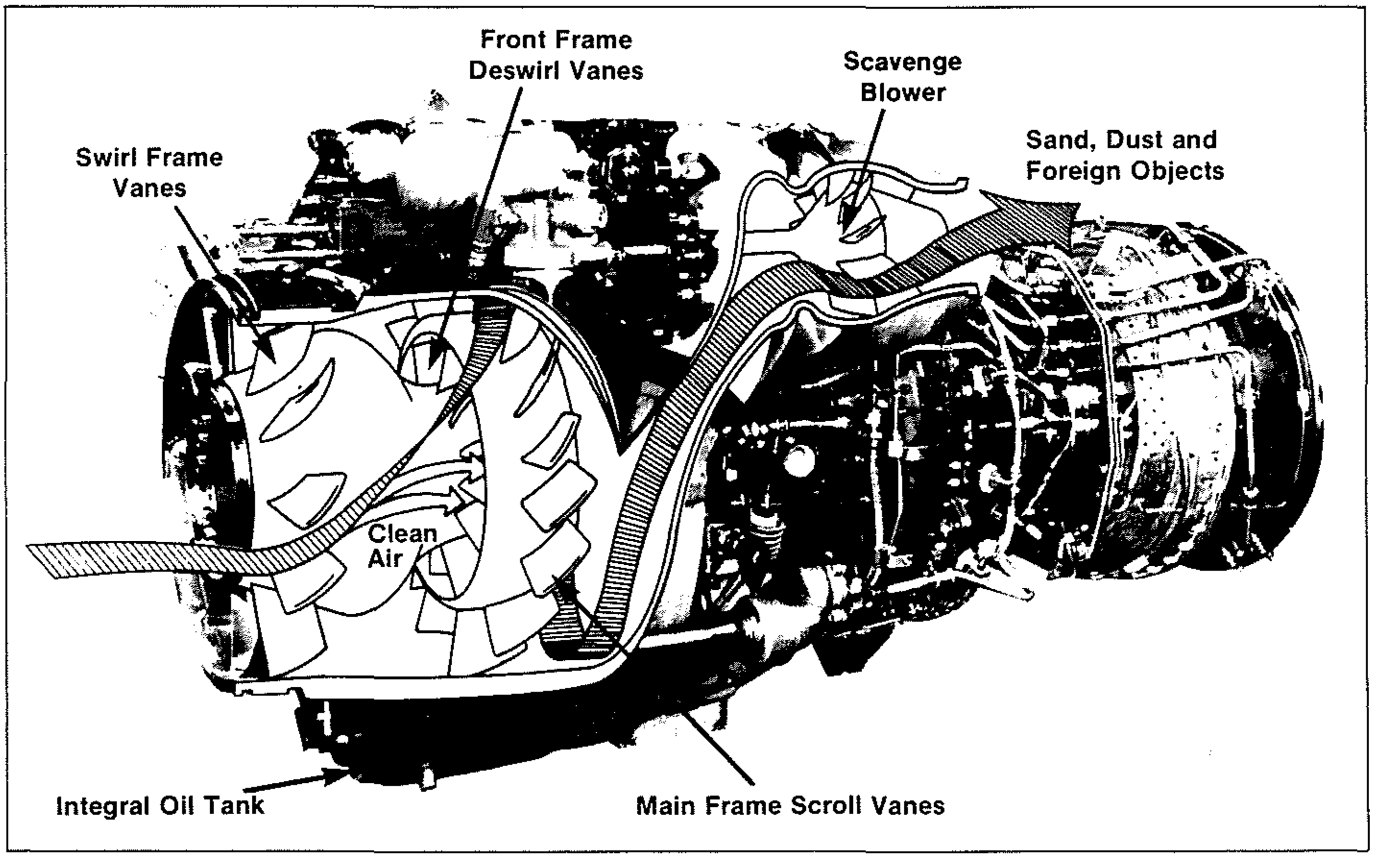

Figure 1 — Inlet Particle Separator

core air prior to entering the compressor inlet guide vanes.

The frame also forms the splitter nose at the dividing point between scavenged air and compressor core air. At the junction of the inner flow path and the swirl frame, an air-activated lip, or "rain step," is formed to trip water from the surface and project it radially outward into the scavenge system (Figure 3).

Main Frame

The cast aluminum main frame incorporates the oil tank, engine mounting pads and the separator scavenge system flow path. Aerodynamically-shaped struts located in the scavenge flow path turn the swirling contaminated air tangentially into the scroll casing. These struts carry return oil from the bearings and gearbox in order to cool the oil and evenly heat the frame.

The scavenged air passes around the scroll and exits through the blower. The cooling surface of the Electrical Control Unit (ECU) is located at the six o'clock position and extends into the scroll casing to provide cooling for solid state components.

Blower

The scavenge blower (Figure 2) is designed to extract 16% of engine inlet airflow at maximum power, operating at 29,000 rpm. The blower is driven by the accessory gearbox and uses a very rugged cast stainless steel impeller with six vanes supported by a grease-packed bearing.

Alternate vanes of the impeller are longer with more forward leading edges. The longer vanes are double the thickness 4.0 mm (5/32") of the others and have shown exceptional resistance to damage from sand erosion and foreign objects.

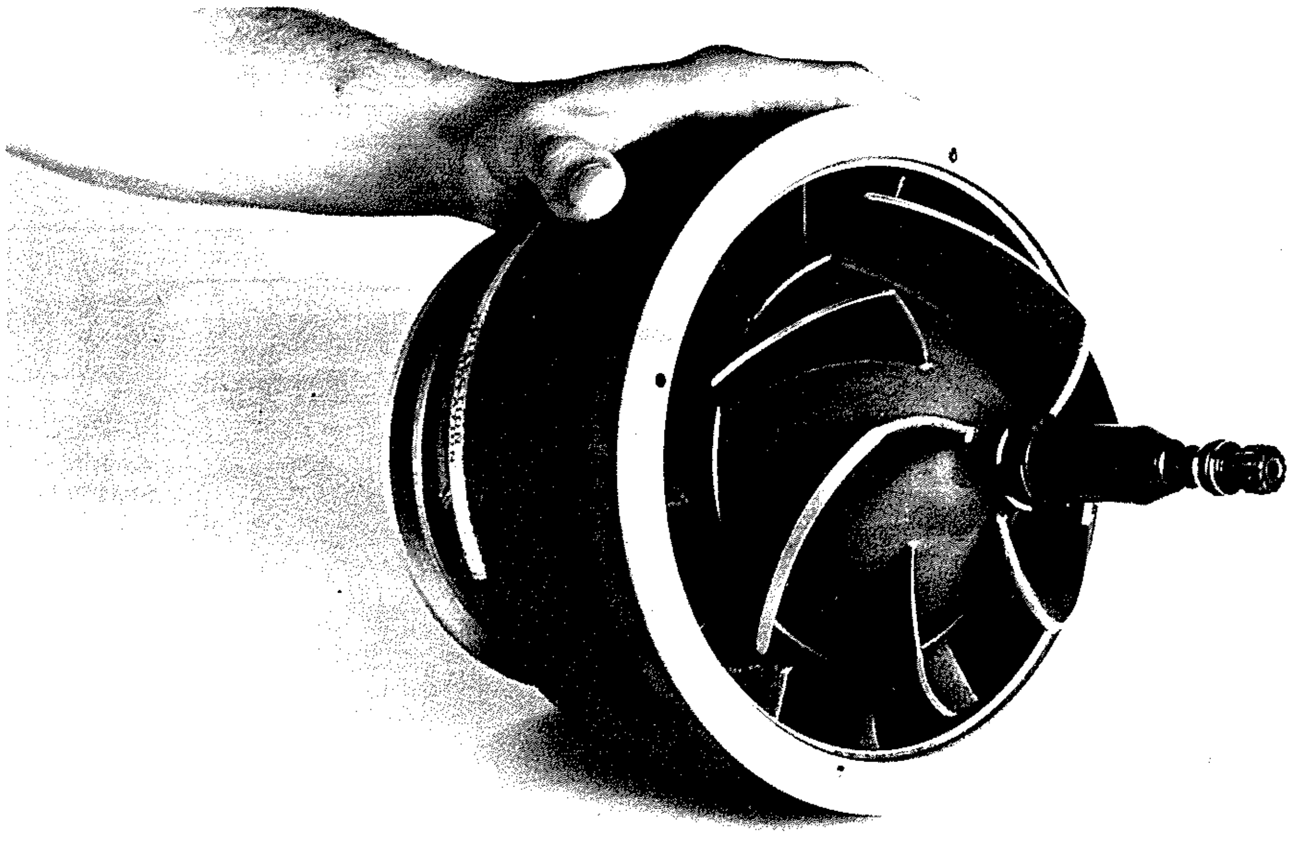

Figure 2 — Scavenge Blower

Anti-Icing

The T700 engine meets all military and FAA anti-icing criteria and has been extensively evaluated in factory test and field operations.

Anti-icing is achieved by hot oil passage and by interstage compressor bleed air that is modulated in proportion to engine speed to reduce performance loss.

In Figure 3 it can be seen that oil in the oil tank and oil passing through the frames anti-ice the main frame and front frame flow paths. The anti-icing/start valve feeds compressor bleed air to the inlet guide vanes, to the splitter nose and to the swirl frame. This circuit is also used to bleed compressor air during starting.

Integration

The aerodynamic flow paths and mechanical blower of the separator have been completely integrated into the basic engine structure. The separator structural frame also encompasses

- Output drive shaft mounting pad
- Three alternate main mounting pads
- Integrated wrap-around oil tank and filler
- Emergency oil supply
- Accessory gearbox mounting and radial drive
- Inlet guide vane mounting
- Anti-icing passages
- T2 sensor location
- Integral air/oil cooler
- Electrical control unit cooling

The integration of the separator in this manner dramatically simplifies installation, eliminates the need for the airframer to provide engine protection and reduces aircraft space needed for the separator. Engines are also less susceptible to FOD caused by maintenance activity on airframe-provided separators.

And, it should be noted that T700 performance quotations are based on an engine with an integrated separator; therefore, the aircraft is not degraded in performance as happens when protection kits are added to unprotected engines.

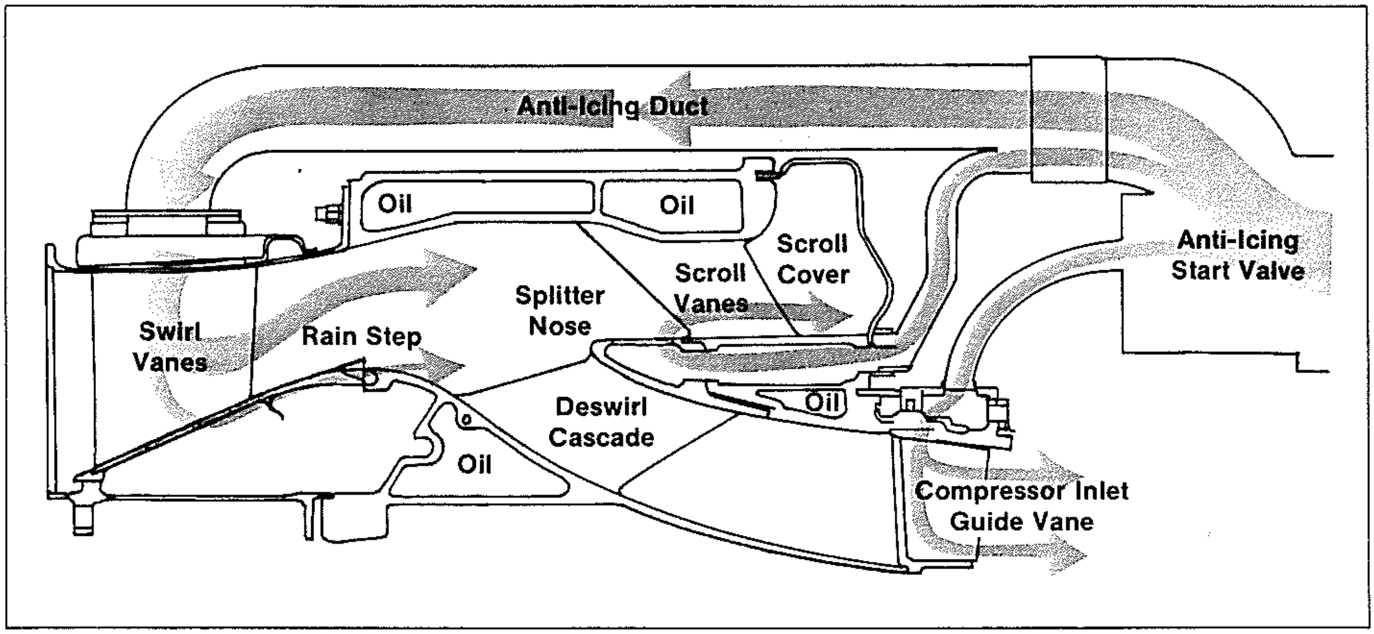

Figure 3 — Anti-Icing System

Requirements

The sand separation requirements for the separator were set by the U.S. Army. The standards include no more than a 15% power loss while operating for 50 hours in air contaminated with "C" spec. sand of a concentration of 52.9 x 10^{-6} Kg/m^3 (3.3 x 10^{-6} pounds/ft^3). This is judged equivalent to 3,000 landings in sand. Additional standards were set by General Electric and included engine weight, inlet loss, structural considerations and corrosion resistance.

T700 Separator System Criteria

• Engine Weight	+8%
• Engine Cost	+7%
• Engine Inlet Performance Loss	Up to 3%
• Anti-icing "on" Performance Loss	6.2% SHP at Max. Power 4.2% SFC at Cruise Power
• U.S. Army Key Requirement:	Sand Protection
— "C" Spec: 94% Efficiency	0-1,000 micron
— "AC" Coarse: 85% Efficiency	0-200 micron
• Scavenge Flow	16% at Max. Power
• FOD Protection	FAA Standards

To maximize FOD protection, the scavenge passages are large enough to pass the largest object, 34 mm dia. (1.35 inch), which could pass through the cascade to the compressor. This prevents large foreign objects from bouncing around the splitter nose and entering the core.

General Environmental Protection

Sand and Dust

Helicopters continually operate from beaches and unprepared sites where clouds of sand and dust are churned by the rotor down wash. This contaminated air is ingested by the engine and, if unprotected, compressor performance rapidly deteriorates. The T700 in U.S. Army use is exposed daily to unprepared sites and hostile terrain (Figure 4).

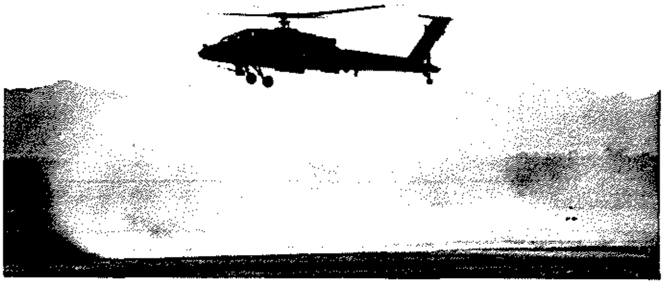

Figure 4 — AH-64 Landing in Sand

Initial design of the separator focused on optimum "C" spec. and "AC" coarse sand separation efficiency while minimizing inlet pressure loss and horsepower extracted by the blower. The final production design has been qualified by testing, using "C" spec. sand.

With the engine at maximum continuous (MC) power, 35 Kg (78 lb) of sand was ingested in 58 hours. During a second evaluation, 40 lb of "C" spec. sand was ingested in 25 hours. The leading edges of the compressor rotor blades were then benched and the shroud coatings repaired. A re-test showed that 40% of original horsepower loss was regained. The performance loss experienced in these tests is compared in Figure 5 with the results of tests conducted with unprotected T58 and T64 GE engines.

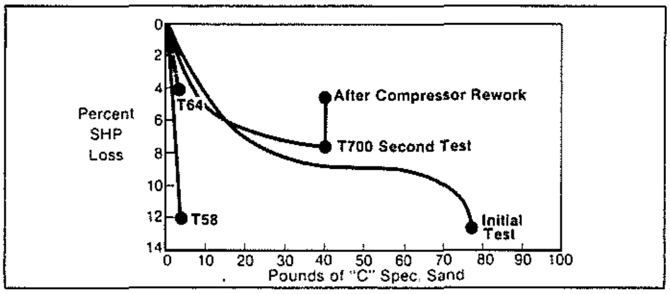

Figure 5 — Pounds of "C" Spec. Sand Ingested Versus Power Loss

Because different types of sand are ingested during operation in different parts of the world, a series of separation tests were made with closely controlled sand sizes. The particle distribution of spec. sand is shown in Figure 6.

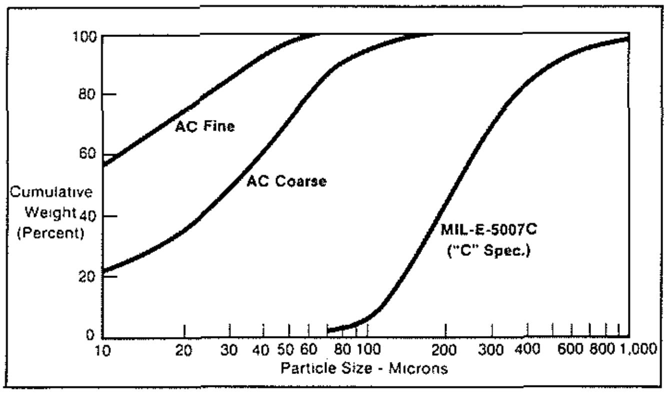

Figure 6 — Spec. Sands Particle Size Distribution by Weight

Figure 7 shows the separator efficiency versus micron size and demonstrates how very fine sands (less than 20 micron) follow the air stream due to aerodynamic drag, heavy particles are momentum-oriented and mid-range sand (20-70 micron) is centrifugally influenced. The small drop-off in efficiency above 70 micron is attributed to bounce characteristics.

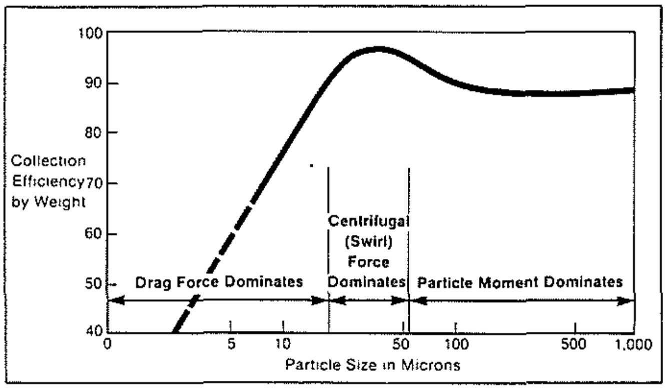

Figure 7 — Separator Sand Collection Efficiency Versus Particle Size

Foreign Object Damage (FOD)

In order to test the capability of the sand and dust separator to protect the engine from common FOD, a selection of 138 objects were introduced in a random manner at the inlet in a component test facility. The objects included nuts, bolts, lockwire, sockets and Allen-type wrenches (Figure 8). The chart (Figure 9) shows that 93% (128) of the objects were separated. Three flow levels were selected for each series of tests, which span the T700 flow range from start-up to maximum. During the first 21 months of U.S. Army operations with the Black Hawk (UH-60A) helicopter, only four engines were removed for foreign object damage. This experience compares favorably with other externally protected helicopter engines and is far superior to unprotected engines. This period included Nap-of-Earth and training missions at various unprepared locations in the U.S.A. and in Panama.

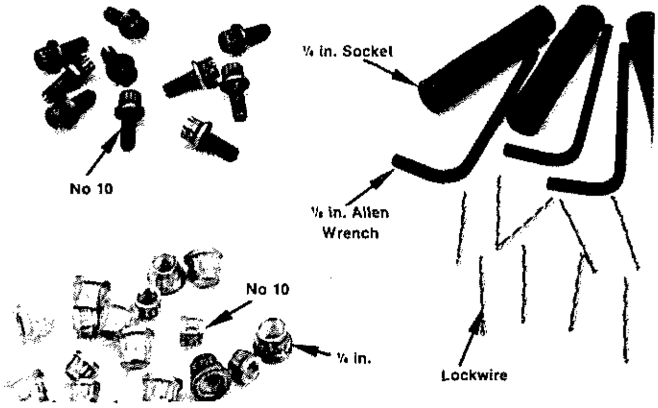

Figure 8 — Typical Foreign Objects

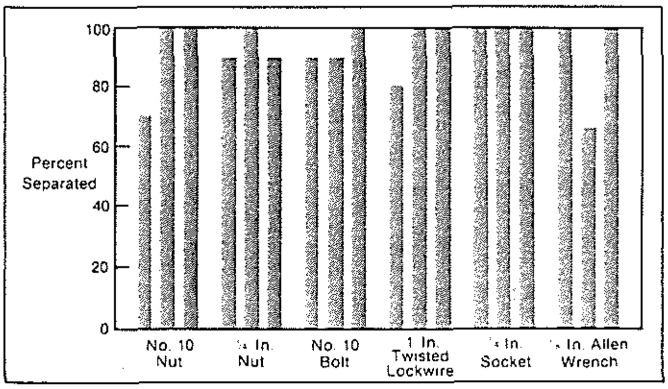

Figure 9 — FOD Separation Efficiency

Bird Strikes

When an engine is struck by a bird, there is the potential for a number of subsequent events. The engine may suffer an In-Flight Shutdown (IFSD) due to compressor stall from inlet blockage (small engines and big birds), major mechanical damage, or less severe permanent or transient In-Flight Power Loss (IFPL) due to inlet distortion or minor mechanical damage.

Bird ingestion testing for the U.S. Army and FAA certification included 0.065 Kg (2.3 oz) birds at 188 Kts and a 0.79 Kg (1.74 lb) bird at 124 Kts.

The two small birds were ingested simultaneously and caused no change in operating parameters.

The large bird, with a 0.6 meter (2 ft) wingspan, caused a 0.4 second recoverable stall and partially lodged in the inlet. The engine continued to operate satisfactorily, and after removing the bird parts, was found to have suffered only a 4.3% horsepower loss. Debris of the bird recovered from the scavenge exit and lodged in the separator amounted to 72% by weight. The large surge margin of the T700 compressor allows minimum operating impact caused by inlet bird blockage following bird strikes.

There have been reported bird strikes in the field but no engine event has been noted. In one reported incident, routine inlet inspection at a U.S. Army base revealed parts of a bird successfully separated. The bird was identified as a starling with a live weight estimated at .085 Kg (3.0 oz). Figure 10 shows the bird lodged against the splitter lip.

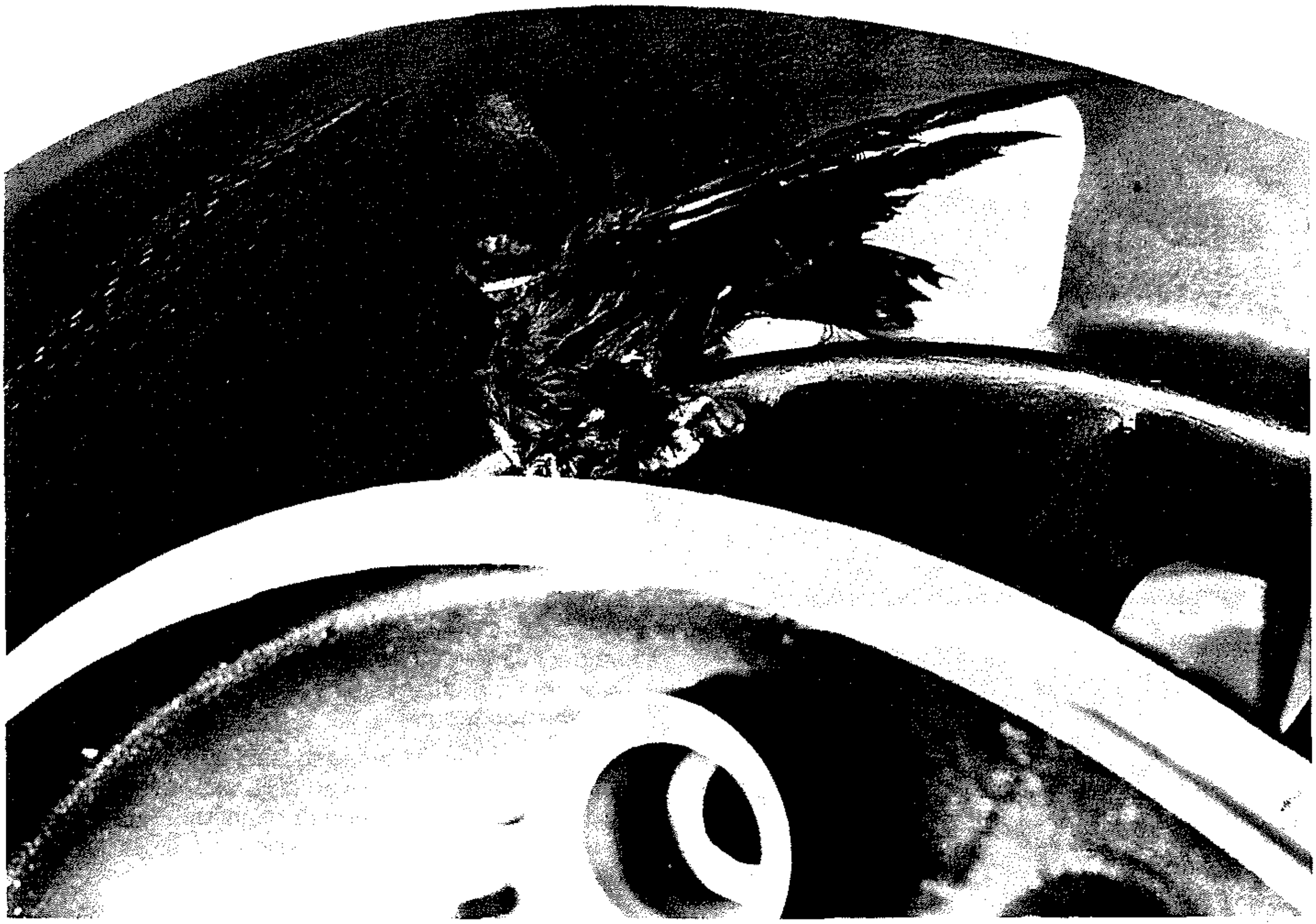

Figure 10 — Bird Strike

Water and Ice Ingestion Protection

Rain, Water and Slush Ingestion

The T700 Inlet Particle Separator has also been found to effectively separate water and slush. Testing for U.S. Army and FAA certification included simulated torrential rain of up to 5% of engine airflow weight with 50% concentration around 120° of the inlet for a period of 3 minutes. The engine showed only light compressor rubs after the test.

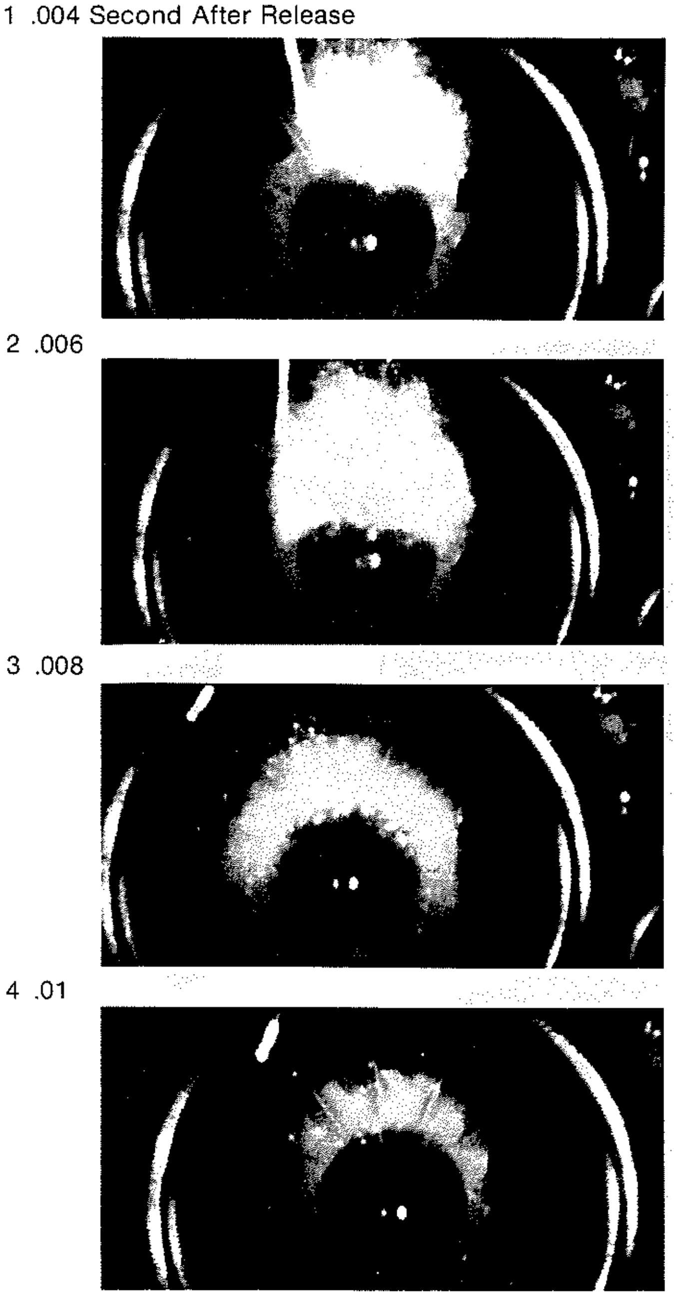
1 .004 Second After Release
2 .006
3 .008
4 .01

Figure 11 — Slush Simulation Test

In order to simulate slush ingestion of the type that caused frequent flame-outs of OH-58 helicopter engines in West Germany, large quantities of water were dropped into the engine inlet. In the planned slush simulation test, 470 ml were instantaneously absorbed by the engine without power loss or engine damage although recoverable stall was detected by instrumentation. The high speed photographs reveal that water inundated the inlet and represented an instantaneous ratio of 1:1 water/air (Figure 11). A large volume of water was separated and passed through the scavenge blower exit.

Salt Water Mist

Both U.S. Navy and British Royal Navy ASW helicopter operators have experienced problems with rapid compressor fouling due to salt buildup while hovering close to the ocean. This rapid buildup causes performance deterioration (up to 15% in an hour) and ultimately can result in engine stalls during aircraft maneuvers. Various T700 engine tests have demonstrated that the integral engine separator is not only remarkably efficient with small sand particles, but it also effectively separates salt water droplets of the same size range.

Salt water corrosion testing conducted by the U.S. Navy using a fine salt spray facility (up to 10 micron) which are not separated efficiently, showed a need for water wash approximately every 1.5 hours in order to regain a 6% horsepower loss.

A number of in-flight surveys show that the majority of salt water droplets encountered during typical hovering over heavy seas range from 25-100 micron. During U.S. Navy testing utilizing salt spray with 25-40 micron droplets, the engine ran 70 hours before its first water wash (5% horsepower loss) was required.

Based on the results of these tests and field experience, the inlet particle separator should provide a high degree of protection and flight safety for all naval helicopter missions.

Icing

The T700 inlet particle separator is fully certified to FAA standards for operation during icing conditions as severe as 1.08 gram/cubic meter (H_20) at -30° C (-22° F). Engine tests conducted in a U.S. Navy environmental tunnel have demonstrated that the engine is able to operate in the most severe icing conditions.

Fully Anti-Iced

Tested and Qualified	1.0 gm/m^3 (H_20) at -20° C 2.0 gm/m^3 (H_20) at -5° C
FAA Certified	1.08 gm/m^3 (H_20) at -30° C

The fully anti-iced separator has a significant flight safety advantage over aircraft-mounted separators that require bypass doors to open when icing occurs and thus exposing the unprotected engine to potential ingestion of shed ice. Shown in Figure 12 is an ice-choked airframe-mounted separator following an icing test. The success of the T700 design has been confirmed during Black Hawk helicopter operations under a variety of icing conditions in Alaska and in other locations. The design has been further evaluated in flight tests behind artificially-produced icing conditions (Figure 13).

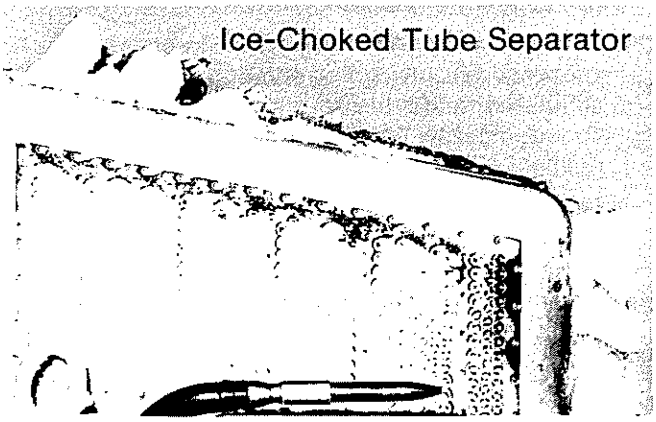

Figure 12 — Non Anti-Iced Separator

Figure 13 — Black Hawk Icing Evaluation

Ice Ingestion

Helicopters operating in icing conditions are constantly exposed to the risk of hard ice engine ingestion usually shed from rotors or fuselage surfaces. Engine structural integrity and possible In-Flight Shutdown (IFSD) or In-Flight Power Loss (IFPL) is always a concern.

The T700 separator has proven to be very successful in protecting the engine in actual and simulated field tests. In order to withstand high-speed impacts, the T700 swirl frame is made from resilient high strength stainless steel.

During qualification testing, ice balls and slabs were ingested by the engine at maximum continuous power with no change in engine operating parameters and no subsequent engine damage.

Large ice balls 51 mm dia. (2") (Figure 14) and smaller balls 26 mm dia. (1") were fired into the engine at 276 Kts. Slabs of ice approximately 76 mm (3") x 229 mm (9") x 6.4 mm (¼") were ingested at low velocity to represent fuselage shedding.

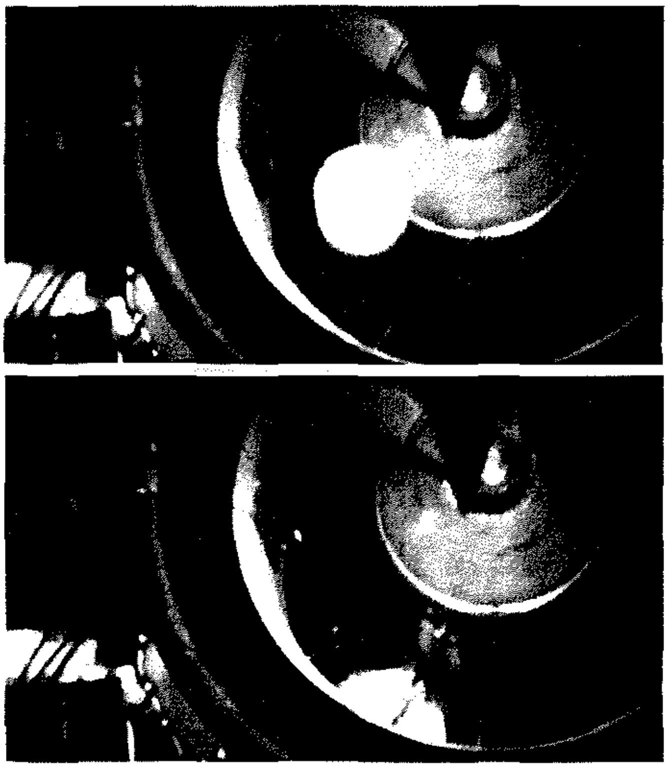

Figure 14 — Large Ice Ball Ingestion

The Black Hawk helicopter has operated at many sites in icing conditions. The pictures in Figure 15 show shed ice entering the engine during helicopter icing tests in Minnesota. There was no engine incident or damage.

Figure 15 — Black Hawk Rotor Ice Shedding

Westland/GE Inlet Integration

The British Royal Navy conducts its ASW and rescue missions in some of the most intensive icing conditions in the world. Historically, nearly half of all engine FODs suffered by the Sea King were due to ice ingestion. The unacceptable rate of FOD due to this singular cause has led to the development of the Gnome engine air inlet icing protection system that allows limited exposure to potential ice ingestion.

As a result of the experience with the Gnome system and because the new WG.34A/EH-101 anti-submarine warfare helicopter will also be operating in this ice intensive environment, Westland and the Royal Navy have focused their efforts on the development of a total helicopter and engine-inlet anti-icing system that will virtually eliminate the possibility of damage due to ice ingestion.

The WG.34A is an advanced demonstrator aircraft being utilized to evaluate key dynamic systems components in advance of the full UK/Italian EH-101 development program.

An important part of the development effort included a Westland/GE ice ingestion test that determined the degree of core engine protection offered by the T700 inlet particle separator when combined with the WG.34A inlet. The testing took place in December 1979 at Lucas Aerospace, Artington, United Kingdom.

The Lucas facility is a refrigerated tunnel which modulates simulated core engine airflow and blower scavenge flow. Because both airflows are refrigerated, ice particles discharged from the core engine and from the blower can be captured and preserved. Thus, fairly accurate separation efficiencies (by weight) can be computed, and the number and size of particles ingested by the core engine can be measured.

Ice Ingested

• Cubes	13 mm and 25 mm (½" and 1")
• Rods	6.4 mm x 6.4 mm (¼" x ¼")
• Slabs	228 mm x 76 x 6.4 mm (9" x 3" x ¼")
• Cones	51 mm dia. x 51 mm (2" dia. x 2" high)
• Slush	500 ml quantities

Nylon mesh netting [0.76 mm dia. (.030"), 2.5 mm (0.10") x 3.17 mm (0.125") opening] was used to capture ice particles in both air streams. "Calibration" testing showed that about 30% (by weight) of the particles escaped from the blower scavenge and core engine collection nets. An engine inlet particle separator was used for this test with a facility scavenge blower. Engine flow path hardware involved separator hardware only and anti-ice and oil system heating were not simulated during the component testing.

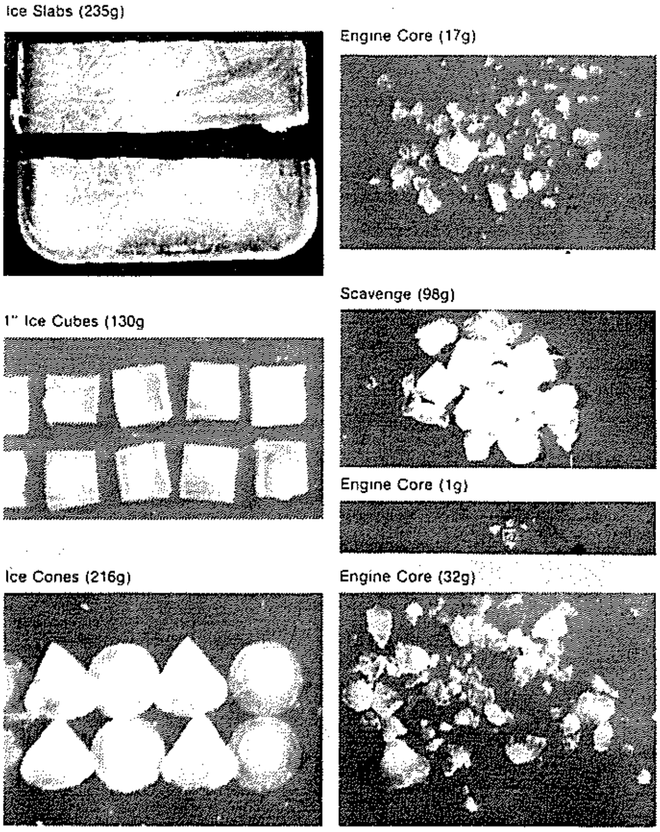
Ice Slabs (235g)
Engine Core (17g)
1" Ice Cubes (130g
Scavenge (98g)
Engine Core (1g)
Ice Cones (216g)
Engine Core (32g)

Figure 16 — Ice Ingestion Examples

Separation Efficiency Results

The first series of component tests were conducted as a collection-efficiency baseline. A standard inlet bellmouth was used and was mounted on the engine/separator hardware. Although a variety of core engine airflows were utilized, the most pertinent results were obtained at a simulated 5-hour cruise power condition (Figure 16). The 5-hour cruise power condition is a critical test condition because it will be typical of Royal Navy ASW operations with the EH-101.

This test baseline showed consistently high separation efficiency on all types of particles except for the ice cones. The artificial cone shapes were not easily broken up at low speed and stuck between the scroll vanes. When they finally worked loose inside the separator, their trajectories were subject to random bounce patterns and thus gave lower collection-efficiency results.

Baseline Separation Efficiencies
Results at 7.5 lb/sec.

Cubes 97.8%	Cones 84%	Slush 92.3%
Rods 98.2%	Slabs 97.5%	

The bellmouth inlet was removed and the WG.34A side facing inlet was mounted on the engine/separator hardware (Figure 17). When ice and slush were injected directly into the WG.34A inlet, the data showed that the side facing inlet did not alter bellmouth inlet baseline collection efficiencies of the engine separator.

However, the Westland inlet considerably enhanced the overall ice ingestion protection of the system. The side facing inlet not only provides complete line of sight protection in forward flight but careful aerodynamic design has also reduced inlet face velocities to a level that avoids capture of ice in very close proximity. This secondary advantage provides very desirable protection from ingestion of shed ice while at hover, on the ground or on ship deck and at low flight speeds.

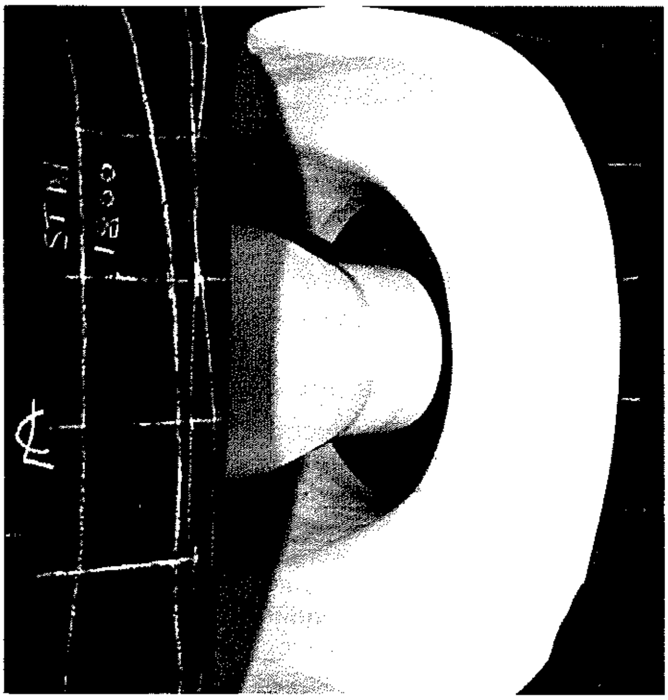

Figure 17 — Westland WG.34A Inlet

Despite the 90° bend in the Westland inlet, a rigorous analytical and wind tunnel program conducted by Westland reduced inlet losses and distortion to levels equal to other T700 installations.

The combined system, of minimizing ice entering the inlet and a high efficiency separator on the engine, will provide the EH-101 with a very high degree of FOD engine protection. Also, the system will be completely anti-iced and require no bypass mechanisms.

Advanced Separator Concepts

GE is continuing to evolve other separator concepts that could be integrally incorporated into the T700 and other advanced turboshaft engines. Two of the most promising concepts have recently undergone preliminary component and demonstrator engine evaluation. One is an Axial Flow Separator, the other is the Booster Stage Separator.

Axial Flow Separator

The axial flow separator shows considerable promise as a means of reducing cost, complexity and performance penalties while providing a high level of separation with larger particles and foreign objects. Some tradeoff with collection efficiency of smaller particles has been experienced; but because large particles are responsible for accelerated airfoil erosion and are ground into fine particles as they pass through the compressor, it becomes beneficial to maximize their initial separation.

An attractive cost-reducing advantage of the axial flow separator is that the larger number of swirl and deswirl vanes are replaced by standard structural struts and separation is achieved by aerodynamic acceleration, particle momentum and core passage line-of-sight shielding. For weight reduction and improved fuel efficiency, a down-sized scavenge system is used (Figure 18).

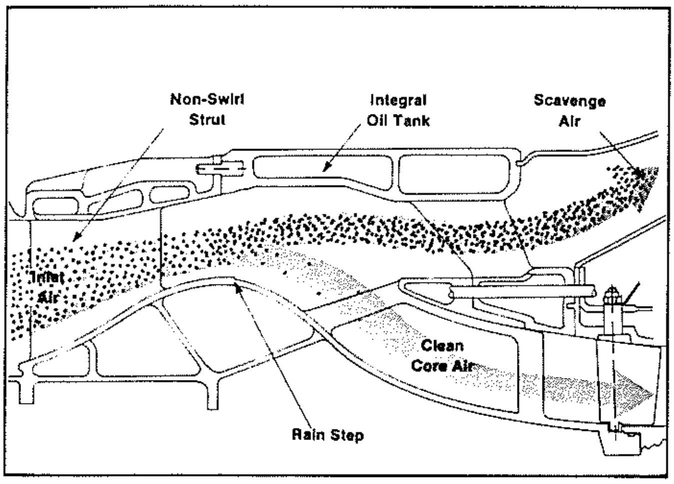

Figure 18 — T700 Axial Flow Separator

Booster Stage Separator

Outfitted with a low pressure turbine-driven booster stage, the current T700 engine has operated for 200 hours and demonstrated more than 2,000 HP. By integrating the booster stage with a scavenge flow duct, used also for matching booster stage and core flow, the booster separates sand, dust and foreign objects. Proper systems design has enabled a significant engine growth step to retain an efficient fully integrated particle separator system (Figure 19).

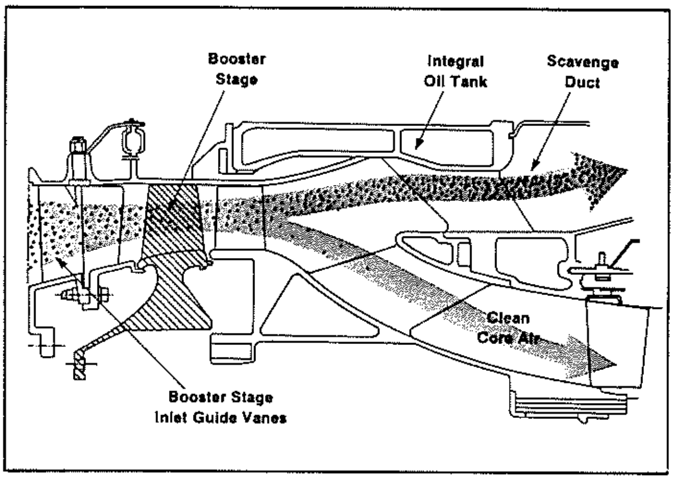

Figure 19 — T700 Booster Stage

Summary

Considering the fact that U.S. Army helicopter powerplant development has focused on long-term survival with concentrated sand ingestion, properly designed engine inlet separators also provide excellent engine protection under all environmental conditions. The integral T700 separator has been thoroughly tested and proven effective against operating hazards caused by salt water mist, FOD, birds, rain and slush and hard ice ingestion.

The integral inlet separator concept is the optimum solution for helicopter propulsion systems designed to produce uncompromised performance in icing conditions. Beginning with realistic component testing to guide preliminary design, a comprehensive integrated aircraft/engine test program will ensure optimum installed engine protection.

Various integrated inlet particle separator concepts allow powerplant designers the flexibility to make some significant tradeoffs of aircraft performance versus core engine protection.

The T700 represents a significant advance in engine tolerance of adverse environmental conditions and promises new levels of reliability, durability and low life cycle cost for modern military and commercial vertical lift aircraft.

Recognition

GE wishes to acknowledge Westland Helicopters for their leadership and cooperation in successfully completing the WG.34A inlet/T700 separator component integration program, November-December 1979.

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Integral Engine Inlet Particle Separator
Report No. USAA MRDL-TR-75-3/A, Vol. 2-31B

GENERAL ELECTRIC

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