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Abstract

The U.S. Army Research Laboratory, NASA Glenn Research Center, and Rolls-Royce Allison are working collaboratively to demonstrate the benefits and viability of a wave-rotor-topped gas turbine engine. The self-cooled wave rotor is predicted to increase the engine overall pressure ratio and peak temperature by 300% and 25 to 30%, respectively, providing substantial improvements in engine efficiency and specific power. Such performance improvements would significantly reduce engine emissions and the fuel logistics trails of armed forces. Progress towards a planned demonstration of a wave-rotor-topped Rolls-Royce Allison model 250 engine has included completion of the preliminary design and layout of the engine, the aerodynamic design of the wave rotor component and prediction of its aerodynamic performance characteristics in on- and off-design operation and during transients, and the aerodynamic design of transition ducts between the wave rotor and the high pressure turbine. The topping cycle increases the burner entry temperature and poses a design challenge to be met in the development of the demonstrator engine.

Introduction

The wave rotor is a self-cooled dynamic pressure exchange machine that can be embedded concentrically within a gas turbine engine to increase engine overall pressure ratio by 300% and peak temperature by 25 to 30% while maintaining rotating machinery temperature levels consistent with conventional materials and cooling technology. The topped engine is predicted to operate with substantially higher fuel efficiency (*i.e.*, lower specific fuel consumption, SFC) and power to weight-flow ratio (SP, cf. Welch *et al.*, 1997). These improvements translate into potential benefits for both the military and civilian sectors. The reduced fuel burn has far reaching implications in terms of the fuel economy and logistics trail of Army missions and, hence, is of strategic importance to the future U.S. Army (Elber *et al.*, 1997). The wave rotor is considered an enabling technology for an alternative path to meet IHPTET (Integrated High Performance Turbine Engine Technology) III goals and beyond. The lower fuel consumption also translates directly into reduced emissions which is a driving factor in global civil aviation (cf. *NASA Strategic Plan*, 1998).

The Army Research Laboratory (ARL), NASA John H. Glenn Research Center at Lewis Field (GRC), and Rolls-Royce Allison are working collaboratively to demonstrate the benefits and viability of a wave-rotor-topped gas turbine engine. A successful wave-rotor/gas-turbine-engine demonstration is a necessary step on the path to mature wave rotor technology. To this end, a demonstrator engine is planned that will achieve significantly improved performance, aggressively incorporate wave rotor technology into the conventional gas turbine engine flow path, utilize current materials and mechanical technology, utilize existing engine hardware to a large degree, and introduce minimal mechanical complexity into the engine (cf. Snyder and Fish, 1996).

The Rolls-Royce Allison model 250 was selected as the baseline engine because of its primary flow path configuration and its engine component modularity, including limited interchangeability and compatibility among the compressor, turbine, and gear boxes of the several engine derivatives in production. This choice reflects the reality of economic constraints and the resulting philosophy for the demonstrator engine project to allow sharp focus on development of the wave rotor without development of any new, adapted, or scaled turbomachinery hardware. When examining production turboshaft engines in terms of SFC at rated power as shown in figure 1, it is evident that incorporation of a wave rotor topping unit into an engine embodying relatively mature technology can result in SFC levels well below those attained by engines that use the state-of-the-art turbomachinery presently on the market.

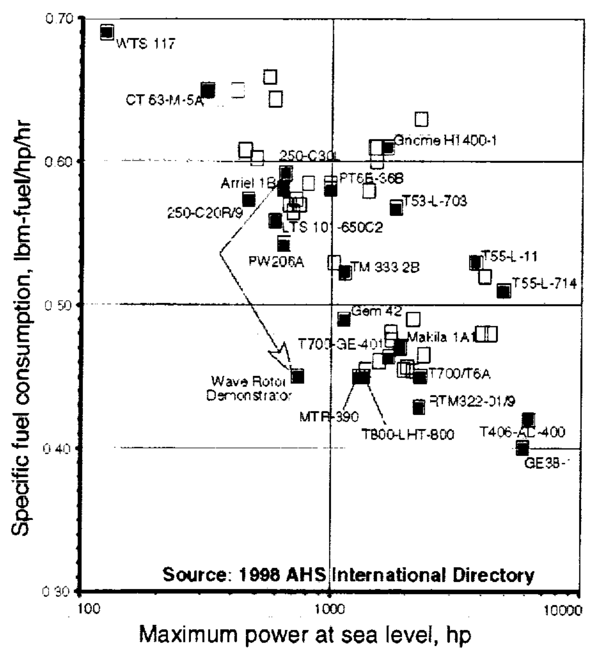


Figure 1.—Predicted enhancement in turboshaft engine performance levels afforded by wave rotor topping.

A summary of progress toward demonstration of a wave-rotor-topped gas turbine engine is reported in this paper. Descriptions of the wave rotor component and predicted benefits from cycle studies of the wave-rotor-topped engine are first provided. The important results from two contracted efforts performed to date by Rolls-Royce Allison for NASA GRC on a wave-rotor-topped Rolls-Royce Allison model 250 engine, including details of the preliminary design and layout of the engine and the aerodynamic design of transition ducts between the wave rotor and the high pressure turbine, are then provided. An on-going preliminary mechanical design and structural analysis of the rotor is then described. Finally, future design challenges are discussed.

Description of Wave-Rotor-Topping Cycle for Gas Turbine Engines

Aeropropulsion Engine Application

The wave rotor is a machine designed to exchange energy efficiently between gas streams of differing energy density and, outside of the United States, is often referred to as a pressure-exchanger, energy-exchanger, or Comprex®[1]. Its operating principles and rich history have been described in detail elsewhere (see Azoury, 1992 and Kentfield, 1993). Interestingly, a wave rotor was first applied in a topping cycle for a locomotive gas turbine engine (GTE) shortly after World War II (Meyer, 1947) and only later was a subject of research and development for aeropropulsion (*e.g.*, see Goldstein *et al.*, 1958). General Electric (ca. 1958-1963) and Rolls-Royce (ca. 1968-1972) tested wave rotors with the intention of topping or replacing turbomachinery stages of small turboshaft engines like the Rolls-Royce Allison model 250 (cf. proceedings of the 1985 wave rotor technology symposium at the U.S. Naval Postgraduate School, Shreeve and Mathur, 1985). More recent related work was focused on missile applications (Taussig and Hertzberg, 1984) and industrial ground power plants (Zauner *et al.*, 1993). Since 1990, the benefits derived by topping gas turbine engines for aeropropulsion has been a subject of research at NASA GRC. The research effort has included experimental investigations to understand the principal loss mechanisms of the component and to establish its operating map (Wilson, 1997 and Wilson, 1998), development and validation of computational tools for analysis and design (Paxson, 1995, Paxson, 1996, Welch, 1997b, Larosiliere, 1995), development of design/optimization procedures (Wilson and Paxson, 1996, Welch, 1997a), system studies and mission analyses (Jones and Welch, 1996), and a contracted effort with Rolls-Royce Allison toward the demonstrator engine described herein (Snyder, 1996).

[1] Registered trademark of Brown-Boveri.

Component Description

The wave rotor comprises a tip-shrouded rotor as shown in figure 2 that is surrounded by a stationary casing as shown in figure 3. The casing endwalls are penetrated by inlet and outlet ducts that port gases of different pressure and temperature to and from the rotor flow-annuli. The rotor hub, tip-shroud, and blade surfaces define rotor passages. Gasdynamic (shock and expansion) waves are initiated as the rotor passages open and close to the ported flows in a timed sequence set by the rotor speed and azimuthal location and extent of the ports. These waves compress and expand the gas as they propagate through the rotor passages. In the simplest configuration, the rotor passages are straight, at constant radius, and aligned with the axis of rotation; the net shaft power of the machine is zero like any gas generator spool. The rotative speed is set by aerodynamic design trades and the corrected tip-speeds are typically low (*e.g.*, 100 m/s [300 ft/s]). Although the rotor flow field is inherently unsteady, the port flows are essentially steady and the wave rotor can be closely integrated within other steady flow turbo-machinery components.

Four-Port Wave Rotor for GTE Application

In the GTE topping application, fresh air from an upstream compressor enters the wave rotor through the low-pressure inlet port. This air is compressed by shock waves as it traverses the rotor and cools the passage surfaces. The compressed air is discharged at the opposite end of the rotor to an external burner at a pressure typically three times higher than the compressor discharge. The burner exhaust gas reenters the wave rotor through the high-pressure inlet port. As it traverses the rotor, the hot gas is expanded, heats the passage surfaces, and is discharged to a downstream turbine. The hot gas temperature is typically reduced by 25 to 30% during this expansion process; that is, the burner exhaust temperature is much higher than the turbine entry temperature. The total pressure of the gas delivered to the turbine (*i.e.*, the low-pressure exhaust port) is typically 15 to 20% higher than air delivered by the compressor (the low-pressure inlet port). A detailed description of the four-port wave rotor shown in figure 3 is provided elsewhere (see Welch *et al.*, 1997).

The wave rotor component is compatible with the high temperature, high pressure conditions of the GTE topping cycle application because of several key features:

Self-cooling.—The rotor surfaces are alternatively washed by the relatively low temperature compressor discharge and high temperature burner discharge at frequencies much higher than the material thermal-response-time. The rotor remains substantially (*e.g.*, 25 to 30%) cooler than the burner discharge; therefore, the burner discharge temperature of the topped engine is significantly higher than that of the baseline engine while the rotating component temperatures are comparable.

Low corrected flow.—The component is aerodynamically compatible with the low corrected specific flow rates supplied by the core compressors of modern aeropropulsion engines. The discharge from the full annulus of the compressor diffuser is ducted at nearly constant radius to the partial-annular port of the wave rotor. This flow concentration accommodates aerodynamically efficient rotor passage geometries. Futhermore, the rotor is shrouded so that tip leakage losses are eliminated.

Low Rotative Speed.—Typical wave rotor corrected tip-speeds are a factor of five or six lower than those of modern turbomachines. The simple rotor geometry, the operating temperature, and the need to maintain acceptable hoop stress levels suggest that ceramic rotors may be an attractive design choice (cf. Zehnder *et al.*, 1989).

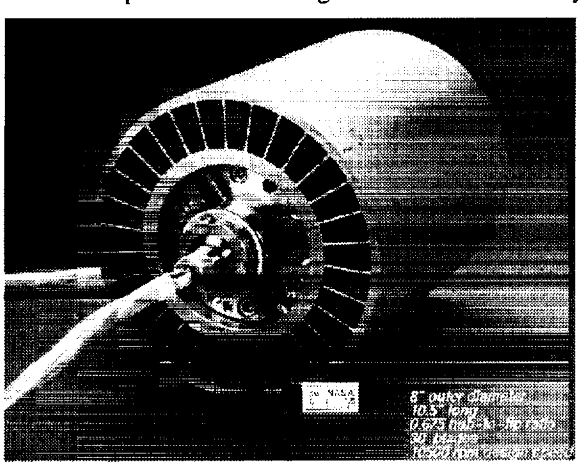


Figure 2.—Rotor of NASA GRC four-port wave rotor experiment.

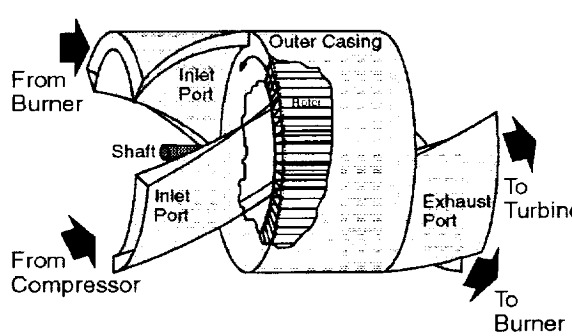


Figure 3.—Four-port wave rotor schematic diagram.

Rapid Transient Response and Stability.—The wave rotor responds (gasdynamically) to transients in adjacent components within a couple of rotor revolutions (*e.g.*, ten milliseconds). The fast response is quite independent of its instantaneous rotative speed, in contrast to turbomachinery components that must spool up or down. The prompt response has been demonstrated in Brown-Boveri's diesel engine supercharger (Comprex®); engines fitted with the wave rotor responded faster to power demand than did the same vehicles fitted with a conventional turbocharger (see Berchtold and Gull, 1960). Past research has suggested that a wave-rotor-topping unit can enhance the dynamic stability of the gas turbine engine (*e.g.*, Taussig and Hertzberg, 1984). A numerical study by Greendyke *et al.* (1997) showed that the wave-rotor-enhanced engine is indeed less likely to surge during rapid fuel flow changes than an untopped GTE. This stabilizing feature may allow wave-rotor-topped engine operation at significantly reduced compressor surge margin.

A formidable set of technical challenges balance these enabling features: leakage flows between the rotor and casing endwalls, noise associated with gasdynamic waves emitted into the ports, high cycle fatigue of both the rotor blades (due to unsteady loading) and the downstream blade rows (due to potential interactions), ducting and associated thermal and mechanical loads, a means to spin the rotor, and the need for the wave rotor to supply high-pressure-turbine cooling air in some engine applications. The technical challenges are being identified and addressed in a step-wise manner through the systematic research program at NASA GRC and are addressed to some degree in the conceptual design of the demonstrator engine.

Overview of Progress Toward Demonstrator Engine

Evaluation of the notional demonstrator engine project began with system studies at NASA GRC and at Rolls-Royce Allison. The assumptions made for component performance are continually assessed in the light of lessons learned from the in-house experiments and analysis mentioned above. Concurrently, a general layout and preliminary design study of the wave-rotor-topped demonstrator engine is underway which has included detailed analysis of the wave rotor ducting and initiation of the rotor mechanical design and structural analysis.

Wave-Rotor/GTE Concept

A systematic diagram of the Rolls-Royce Allison model 250 is shown in figure 4. This popular helicopter engine is configured such that the centrifugal compressor discharge is ducted to the aft of the engine where it is turned ninety degrees as it enters the combustor. The burner discharges into the two-stage high-pressure turbine (HPT) that drives the compressor. A center gearbox links the low-pressure turbine (LPT) to a power output pad. Exhaust gas is ducted out the top center of the engine. In a wave-rotor-topped configuration of this engine, the wave rotor and associated ducting can be installed between the burner and HPT as shown in figure 5. The wave rotor diameter and length are both approximately equal to the tip diameter of the HPT. In the schematic diagram shown, the wave rotor spins coaxially on a separate shaft at approximately one-third the speed of the gas generator spool through its operating range (cf. Snyder and Fish, 1996). Addition of wave rotor topping inherently requires alteration of the design-corrected flow rates of the HPT. Conveniently, the interchangeablility among the components of the Rolls-Royce Allison model 250 derivatives accommodates rematching with existing components. Within the constraints of project funding levels, the planned demonstrator engine will be a back-fitted, "breadboard" engine rather than a "clean-sheet" design and build; however, the flexibility offered by the baseline Rolls-Royce Allison model 250 family allows for significant enhancement of engine performance levels while using off-the-shelf components as described below.

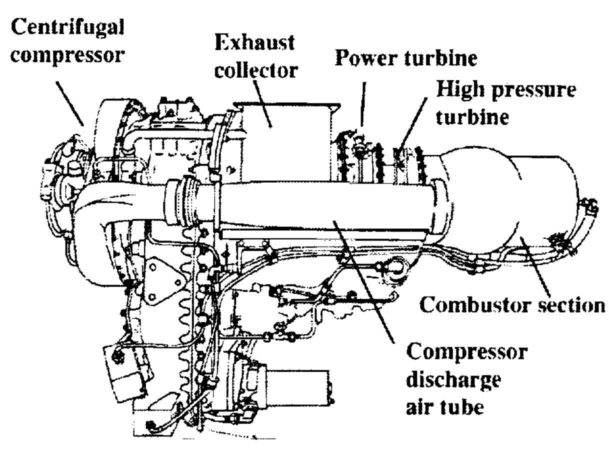


Figure 4.—Rolls-Royce Allison model 250 turboshaft engine.

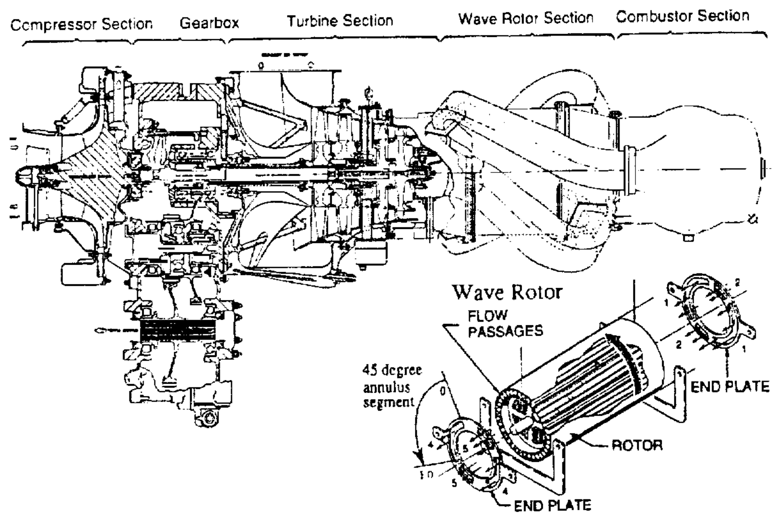


Figure 5.— Demonstrator engine combines wave rotor with modules from existing engine line.

Cycle Analysis

Cycle studies carried out by Jones and Welch (1996) and Snyder and Fish (1996) predicted that wave rotor topping could enhance the SFC and SP of a "clean sheet" Rolls-Royce Allison model 250 engine by approximately -15 to -22% and +18 to +20%, respectively. Recent work at ONERA shows similar predicted benefits (Fatsis and Ribaud, 1997). The total temperature-entropy diagrams for untopped (baseline) and wave-rotor-topped engines shown in figure 6 suggest how these benefits are obtained. The compressor pressure ratio, the burner energy addition, and the HPT inlet temperature are the same for both engines; however, because heat addition occurs at higher pressures and temperatures in the topped engine, and because the expansion and compression work in the wave rotor are equal, the total pressure into the turbine of the wave rotor topped engine is 15 to 20% higher than that of the untopped engine. The higher availability at the HPT inlet translates directly into increased engine power and efficiency.

Wave rotor performance map.—In the cycle decks used, the burner and its associated loss is replaced by the wave rotor/burner topping unit and its associated total pressure gain. The pressure ratio (turbine-entry/compressor-discharge) is represented by a performance map shown in figure 7 that was computed by Paxson using his Q-1-D model (Paxson, 1996). The wave rotor pressure ratio is plotted as a function of corrected rotor speed, flow, and burner heat addition. The rotor geometry and speed were set by the optimization procedure proposed by Wilson and Paxson (1996). For a typical optimized rotor, solidity is near 15, hub-to-tip ratio is near 0.7, rotor length to diameter is near unity, and corrected rotor speeds are near 100 m/s (300 ft/s).

Design point operation.—The compressor surge margin in the wave-rotor-topped engine was maintained equal to that of the baseline engine. It should be noted that for the purposes of the study, no credit has been taken for surge margin enhancement as predicted by Greendyke *et al.* (1997). Relative to the design point of the baseline engine, the wave rotor acts to increase the entry total pressure of the HPT. The resulting decrease in the inlet corrected specific mass flow rate of the turbine (with turbine inlet temperature held constant) was accommodated by replacing the model 250-C30 turbine section of the baseline engine with the turbine section of the model 250-C28C engine (cf. Snyder and Fish, 1996). An additional adjustment of 5% was also allowed by affecting slight modification to specific sets of turbine hardware. In this way, flow matching was accomplished with existing components. The topped engine overall pressure ratio was 23:1 relative to the baseline engine levels of near 8:1. The demonstrator engine was predicted to operate at 547 kW (733 hp) power levels at 12.7 mg/N-s (0.45 $lb_{m\text{-}fuel}$/hp-hr) SFC as compared to the baseline engine operation at 485 kW (650 hp) and 16.7 mg/N-s (0.59 $lb_{m\text{-}fuel}$/hp-hr). While the turbine entry temperature was maintained at the baseline engine level of 1328 K (1930 °F), the burner exhaust temperature of the topped engine is predicted to be 1702 K (2605 °F). Note that the temperature of the gas discharged from the wave rotor to the burner, 1237 K (1767 °F), is significantly higher than the burner inlet temperature of the baseline engine, 848 K (1067 °F). This increase in burner inlet temperature, as well as burner pressure and outlet temperature, will require a more advanced burner design than that used in the model 250 production engine. An effusion cooled or Lamilloy®[2] based design along with a change in liner material are candidates for use in the demonstrator test engine. Development of an appropriate combustion system is targeted to be an important segment of the continuing effort toward a successful demonstrator engine.

[2] Registered trademark of Allison Engine Company, Inc.

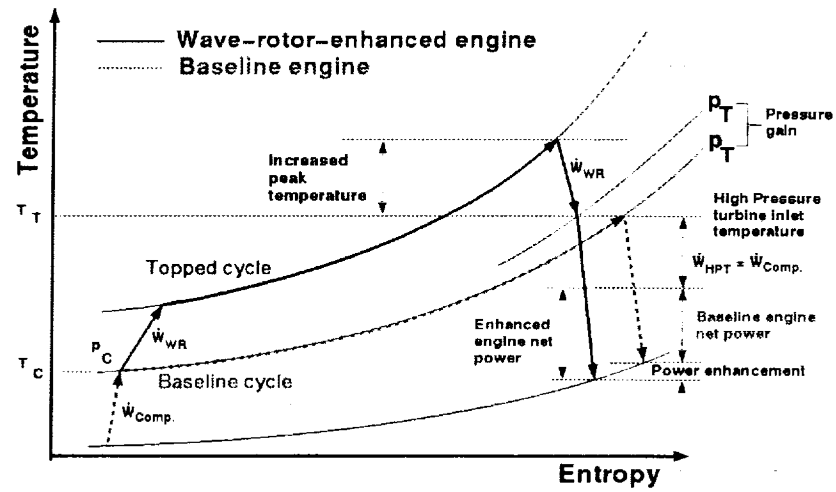


Figure 6.—Temperature-entropy diagram showing thermodynamic benefit of wave-rotor-topping cycle.

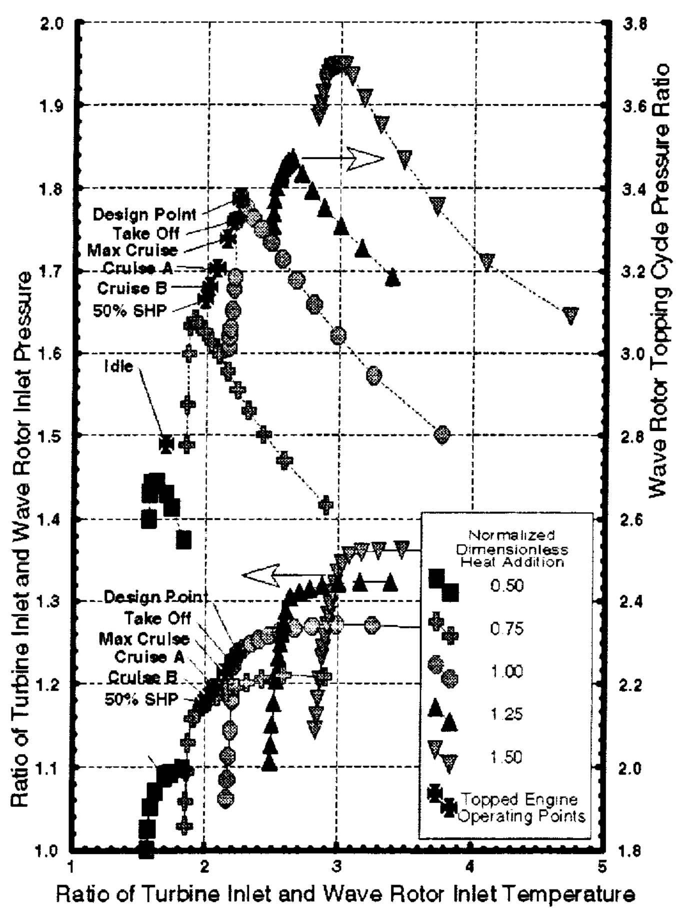


Figure 7.—Wave rotor map with demonstrator engine operating points displayed.

Off-design operation.—The cycle deck model was exercised over six steady-state power settings ranging from idle to take-off power. The wave rotor contributes a nearly constant 3:1 overall compression ratio over the operating line. The corrected rotor speed (free-wheeling) and corrected flow of the wave rotor are essentially constant over the operating line. The predicted SP and SFC of the topped and baseline engines vary as shown in figure 8. Evidently, the benefits of wave rotor topping are maintained at part power. At idle the SP is increased by 19% and the SFC is reduced by 32%; further, a sensitivity analysis showed that engine operation was found acceptable at idle for a range of power turbine speeds. The temperature difference between the burner exhaust and the HPT inlet gas is essentially a constant 330 K (600 °F) from idle to full power; unfortunately, the burner inlet temperature of the topped engine operates between 330 K to 555 K (600 to 1000 °F) higher than the baseline engine over the operating envelope. As mentioned above, these higher temperatures push the burner beyond the technology regime of the baseline engine.

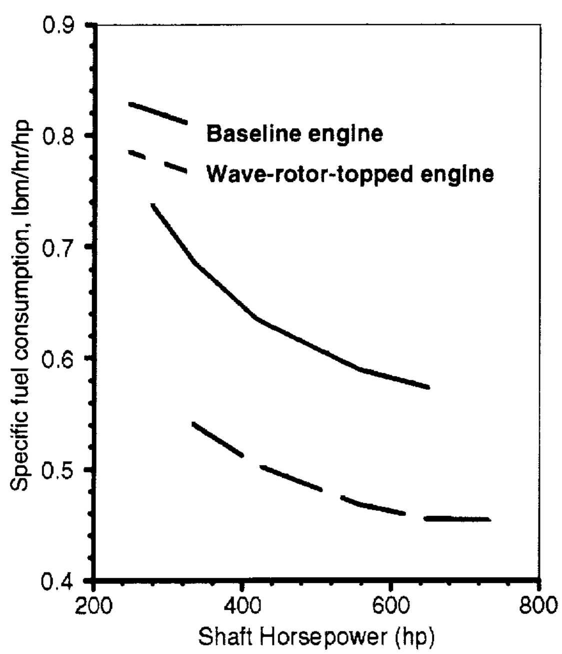


Figure 8.—Off-design performance of baseline and wave-rotor-topped engines.

Preliminary Design and General Layout

The preliminary design work has addressed mechanical aspects of component matching, flow path and component reconfiguration, wave rotor ducting, the advanced combustor design, and identification of the wave rotor component and adaptive engine parts (Snyder, 1996). The major conclusion of the study was that the wave rotor demonstrator engine could be assembled using existing hardware and that the greatest challenge lies in the design of the burner due to the high burner inlet temperatures. Other details of the preliminary design and general layout effort include the following:

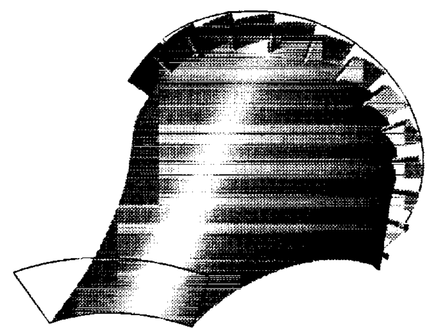
Mechanical components.—The preliminary design and layout indicated that the C30 compressor and C28C turbine units are mechanically compatible and that the gearboxes of the two engine variants are interchangeable. The fundamental layout of the Rolls-Royce Allison model 250 minimizes the impact of the increased thrust on the component because the compressor and turbine thrusts are carried on separate bearings. The performance of the free wheeling wave rotor is found to be nearly optimum; that is, the performance levels of a wave rotor on the passive speed schedule are nearly the same as those attained on a metered speed schedule. The wave rotor can therefore spin on an independent shaft.

Cooling air requirement.—The baseline engine requires approximately 2% cooling within the turbine section. This air is derived from compressor discharge at 625 K (665 °F) and at a supply pressure approximately 4% above the HPT entry total pressure due to the presence of the conventional burner liner pressure drop. In the wave-rotor-topped engine, the compressor discharge air is approximately 20% below that of the HPT entry total pressure. If this engine utilized a highly cooled first stage nozzle or blade employing internal impingement or a serpentine cooling scheme, an alternate supply of cooling air would need to be developed. However, the end-point use pressures of the cooling air of the model 250 engine are significantly below that of the turbine entry total pressure. Thus for the demonstrator engine, modifications to the supply circuit of the cooling air will suffice in delivering required cooling air via bleed from the compressor discharge stream. However, when applying wave rotor topping to a "clean sheet" design engine, established practices of delivery of turbine cooling will need to be reexamined.

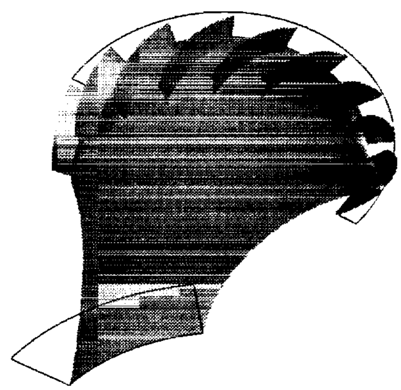
Ducting.—The wave rotor device inherently requires the use of adaptive ducting to rout flows between the partial annular stations at the wave rotor and the typically full annuli at the conventional turbomachine interfaces. These transitions—compressor to wave rotor, wave rotor to burner, burner to wave rotor, and wave rotor to HPT—must occur with minimal aerodynamic loss and yet in a manner that minimizes the length and wetted-perimeter added to the engine. The baseline engine already utilizes a non-annular compressor transfer duct that is very conducive to adaptation to the wave rotor inlet port. The wave rotor component itself sets the allowable pressure loss from wave rotor high-pressure exit port to high-pressure inlet port (burner exit station) at 8.9%. Less than half of this will be typically used across the burner liner, with the remainder able to be attributed to the remaining ducting. The design of this ducting beyond the initial space claim considerations has yet to be addressed. The transition duct between the wave rotor and the HPT was seen to be of critical importance and was studied in detail as reported below.

Detailed Wave-Rotor-to-HPT Transition Duct Design
Common to all wave rotors is the need to port flow between the partial sectors of the wave rotor and the full annuli of the surrounding turbomachinery (see figure 3). A preliminary design and analysis of the transition duct between the low pressure exhaust port of the wave rotor and the HPT was carried out by Rolls-Royce Allison (Gegg and Snyder, 1998 and Weber and Snyder, 1998). The wave rotor has two duct sets. Each transition duct ports half (1.12 kg/s, 0.26 kg/s-corrected) of the engine mass flow rate from a 45-degree sector to a 180-degree half annulus. The turbine half-annulus flow area is nearly twice that at the wave rotor exhaust port. The transition must be accomplished in a short length so as to minimize engine added-length and weight. The flow exits the wave rotor at an average of Mach 0.5 and swirl angle of 19 degrees (from the axis of rotation) and enters the HPT rotor at Mach 0.7 and swirl angle of 65 degrees. To complicate matters further, the wave rotor discharge is highly nonuniform tangentially in total pressure, temperature, and axial velocity. The principal objective of the design was a low $\Delta p_0/p_0$ transition in which the HPT nozzle was incorporated into the ducting to the extent possible. Surface area, length, and weight added to the engine were also important metrics. The initial designs established using the volute procedure of Frolov and Golubtsov (1972) were improved upon by using knowledge gained from the results of 3-D computations with the OVERFLOW code (Buning, 1998).

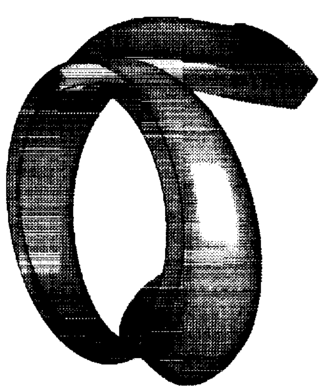
Three duct concepts were considered: diffusing duct followed by the conventional nozzle ring of the model 250-C28 turbine (Type 1); converging duct and nozzle with integral turning vanes (Type 2); and a rapid turning elbow with volute (Type 3). A number of variants were considered within each of the three concepts: co- and counter-rotating wave rotor and HPT turbine, non-diffusing and non-turning sections at the inlet of the duct, and vaned and vaneless volutes. The best performers of the three concepts are shown in figure 9 and important parameters from the study are summarized in table 1. The duct concept in which the flow is diffused before entering the nozzle ring (Type 1) is considered best based on aerodynamic loss levels. The Type 1 duct with a non-diffusing section has $\Delta p_0/p_0 = 3.7\%$ that is only slightly higher than the 3.25% assumed in the cycle studies. The addition of the non-diffusing section increases the duct length and area and in some applications might ultimately push the design choice toward a duct with a shorter non-diffusing length. In addition to higher aerodynamic loss levels, the Type 2 and Type 3 ducts preserve the tangential nonuniformity of the wave rotor exhaust flow; the residual nonuniformities in total pressure and temperature are reflected in the predicted loss in HPT efficiency and large percentage increase in total engine weight to shaft horsepower metric as shown.



(a) Type 1—diffuser with existing nozzle ring.



(b) Type 2—nozzle with integral turning vanes.



(c) Type 3—elbow and volute.

Figure 9.—Designs for each of three types of ducts for transition from wave rotor to high pressure turbine.

Table 1.—Summary of key parameters from transition duct design analysis.

	Type 1		Type 2		Type 3
	Diffuser with baseline nozzle ring		Converging duct and nozzle		Volute
Normalized duct length[a]	1.04	1.46	0.667	1.08	0.667
Normalized duct area[b]	1.92	2.77	1.51	2.23	1.65
Non-diffusing length (% of total duct length)	0	31	50	75	0
Vane count	12	12	5	8	0
Turbine penalty (%)[c]	--	1.1	--	7.8	6.0
%-increase engine weight/SHP	--	4.6	--	27	26
$\Delta p_0/p_0$ (%)	4.1	3.7	5.5	4.9	7.0

[a]duct length divided by wave rotor "rotor" length.
[b]duct area divided by area of baseline engine nozzle ring.
[c]percentage decrease in HPT adiabatic efficiency due to residual temperature nonuniformity.

Rotor Mechanical Design and Structural Analysis

Some past efforts in wave rotor testing have listed mechanical shortcomings including rotor durability as significant issues in making the concept serviceable (cf. Shreeve and Mathur, 1985). Such rotor design issues are currently under detailed examination at Rolls-Royce Allison. The goal of this effort is to develop a preliminary design of the rotating hardware capable of operating in the wave-rotor-topped demonstrator engine previously described. Both the design methodology and the particular rotor design under development for the demonstrator engine constitute new wave rotor technology that is applicable to both the demonstrator and potential engine products. This effort is currently proceeding with identification of a candidate rotor design, preliminary rotor mechanical design, detailed rotor heat transfer analysis, and detailed stress and dynamics analysis.

As stated earlier, the goals of the demonstrator engine effort reach beyond that of just making an engine that will run. The rotor fabrication techniques selected must be suitable for carry over to production hardware with regard to both producibility and ability to meet rotor life.

Novel rotor and bearing mechanical designs are being considered to address rotor end clearance control and thermal growth/stress realities adequately. Currently, the study is addressing the important aspects of rotor dynamics, heat transfer, and stress concerns throughout the rotor on a preliminary basis. Based on one-dimensional transient gas predictions for the aero flow path, this effort will also include a transient analysis of the rotor passage walls in order to determine the potential of thermal stress and thermal shock of the rotor walls. A viable preliminary mechanical design of the rotor is to be identified in the initial stages of the mechanical design effort.

Detailed heat transfer analysis of the rotor at the design-point and during a start-up transient will be conducted to establish the design point rotor temperature and limiting-case thermal gradients in the rotor. Rotor stress and dynamic analysis will include rotational loads, drum internal and external pressure loads, thermal stress loads, and passage way transient pressure/wall dynamic behavior. Life predictions determined according to low- and high-cycle-fatigue, stress rupture, and creep growth allowables will be compared to appropriate rotor life criteria. A refinement to the rotor design will be formulated to conform to the rotor life requirements and life will be verified by revisiting both the heat transfer and stress/dynamics analysis. Limitations on analysis arising from any generic inadequacy of current gas turbine analysis tool capabilities as applicable to wave rotors will be identified.

Summary

The predicted benefits offered by wave rotor topping are significant. The wave-rotor-topping unit is predicted to increase the overall pressure ratio of the baseline Rolls-Royce Allison model 250 engine from 8:1 to 23:1 and burner exhaust temperature by 25 to 30%, leading to predicted SFC reduction of nearly 23% with concomitant power-to-weight-flow enhancement of 13%. The wave rotor demonstrator engine is a necessary step toward the maturation of wave rotor technology for application in aeropropulsion engines. Progress to-date has included detailed cycle analysis, engine preliminary design and general layout, detailed analysis of the critical wave-rotor-to-HPT transition duct, and initiation of rotor preliminary design and structural and thermal analyses.

The anticipated three-year project will require that several technical challenges be overcome. The higher burner inlet temperatures associated with the topping cycle pose significant material challenges for the burner liner. The development of this combustion system, including adaptive ducting and inlet guide vanes between the burner and the wave rotor, is a critical step in the continuing effort toward a successful demonstrator engine.

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13. ABSTRACT ***(Maximum 200 words)***

The U.S. Army Research Laboratory, NASA Glenn Research Center, and Rolls-Royce Allison are working collaboratively to demonstrate the benefits and viability of a wave-rotor-topped gas turbine engine. The self-cooled wave rotor is predicted to increase the engine overall pressure ratio and peak temperature by 300% and 25 to 30%, respectively, providing substantial improvements in engine efficiency and specific power. Such performance improvements would significantly reduce engine emissions and the fuel logistics trails of armed forces. Progress towards a planned demonstration of a wave-rotor-topped Rolls-Royce Allison model 250 engine has included completion of the preliminary design and layout of the engine, the aerodynamic design of the wave rotor component and prediction of its aerodynamic performance characteristics in on- and off-design operation and during transients, and the aerodynamic design of transition ducts between the wave rotor and the high pressure turbine. The topping cycle increases the burner entry temperature and poses a design challenge to be met in the development of the demonstrator engine.

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