Variable Cycle Turboshaft Technology for Rotorcraft of the '90s

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The variable capacity (VARICAP) turboshaft engine minimizes part power fuel consumption by maintaining near-constant turbine inlet temperature and pressure ratio while power is varied by components that change flow capacity. An analytical study, applied to an advanced 2.27-kg/s (5-lb/s), 683-kW (916-hp) turboshaft engine with a turbine inlet temperature of 1477 K (2200°F), is reviewed. Data on two radial turbine geometries tested in a cold-flow rig are also presented. Nozzle area was varied over a flow range from 62 to 120% of design and the performance effects of leakage and cooling injection were quantified. A high-efficiency level was demonstrated over the flow range. The turbine test data were integrated with studies on variable capacity compressors and an engine was synthesized. The results validated the VARICAP concept in showing over 14% specific fuel consumption improvement at 60% power, and consequent large life-cycle-cost savings to a rotorcraft application. The variable capacity engine configuration using moveable sidewalls to vary flow capacity was found to be a viable concept, and a substantial improvement over conventional turboshaft engines.

Introduction

THERE has been a continuing need and effort to lower the system operating costs and reduce the fuel-consumption requirements of turbojet, turbofan, and turboshaft engines. Fuel consumption is especially important in conserving energy resources; it also impacts many important vehicle aspects, including the engine life-cycle cost, engine size, fuel-tank requirements, vehicle payload, and operating costs. The development of high-temperature refractory materials and advances in cooling technology have allowed increases in turbine inlet temperatures.[1] At the same time, increases in simple cycle engine pressure ratios have led to progressive thermal efficiency gains, using advances in computational fluid mechanics[2] and structural design techniques to reduce stage numbers while improving efficiency. Similar advances have been made in the turbine, combustor, and ducting components, and further reduction of fuel consumption by conventional means is reaching the point of diminishing returns; see Fig. 1.[3,4]

Engines are typically designed for a critical or best operating point, while off-design performance characteristics are usually integrated and optimized to suit a given mission. For fixed geometry componentry, this results in an unavoidable specific fuel consumption (SFC) increase at off-design operation. The benefits of variable geometry components to broaden compressor and combustor stability and improve general part power engine performance were studied under a U.S. Air Force-sponsored program in a geared turbofan engine.[5] More recently, the U.S. Army conducted a turboshaft engine cycle study comparing fully variable, simple, regenerative and regenerative plus variable power turbine cycles.[3]

The variable capacity (VARICAP) concept offers the potential of reduced fuel consumption by operating the engine components at or near their optimum conditions over the entire mission, controlling power by varying engine airflow. In the ideal case, design pressure ratio and turbine inlet temperature remain fixed for maximum thermal efficiency. The potential gains of the VARICAP concept rely heavily on achieving a low level of variable geometry losses and minimum leakage penalties at high closures. These inefficiencies are difficult to assess because of the lack of available variable geometry component data. One recommendation given in Ref. 3 was to focus on "research and development efforts on the critical variable geometry loss/leakage issues in compressor, combustor, and turbine components."

Subsequent efforts were extended to the design of a 1588 K (2400°F) cooled variable area turbine,[6] a 1477 K (2200°F) uncooled turbine rotor with a cooled variable area nozzle,[7] an experimental evaluation of the Variable Stator Radial Turbine[8,9] and Variable Area Fabrication and Test programs.[10] The work was sponsored by the U.S. Army Research and Technology Laboratories and directed by NASA. Herein the authors 1) briefly review the results of the latter three programs, 2) integrate the experimental data into the VARICAP cycle analysis, and 3) present the results and performance potentials of the VARICAP engine.

Cycle/Configuration Studies

The first program focused on a cycle optimization, concept evaluation, and detail design of an advanced variable geometry radial turbine with a 2.27-kg/s (5.0-lb/s) airflow size and a turbine inlet temperature of up to 1644 K (2500°F).[7] The turbine was for a rotorcraft application in the early 1990s. Free-turbine and single-shaft engine configurations, with cooled and uncooled turbines, were considered. The variable geometry turbine was to operate at constant speed and constant pressure ratio over a range of flow corresponding to 50-100% of maximum power. The application was to be typical of a rotorcraft engine with a 4000-h life, based on the duty cycle given in Table 1.

Design Point Assumptions and Component Configurations

Compressor Considerations

Single- and two-stage centrifugal compressors and combined axial-centrifugal compressors with a range of pressure ratios from 6.0 to 20:1 were considered in the concept evaluation

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Table 1 Engine Duty Cycle

Rated power, %	% time
100	20
60	50
55	20
35	5
Idle	5

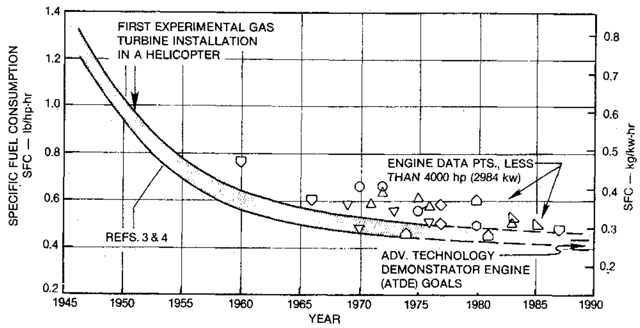


Fig. 1 Diminishing returns on fuel consumption.

phase. High performance over a 50% flow range at constant speed and near-constant pressure ratio was a primary requirement. Variable inlet guide vanes and variable exit diffusers were assumed to be used on all VARICAP configurations. The axial-centrifugal configurations were eliminated early in the study due to an insufficient surge-free flow range potential. The centrifugal stage flow range extension due to the addition of inlet guide vanes or a variable diffuser was estimated from the data of Refs. 11 and 12 as shown in normalized form in Fig. 2. The design point efficiency change with pressure ratio, Fig. 3, was based on prediction logic of Ref. 13, modified for additional losses due to leakages and aerodynamic compromises for variable geometry mechanisms.

Turbine and Hot Section Considerations

Several methods of changing the flow capacity of the radial turbine were considered. Fully pivoted vanes and moveable wall concepts showed the highest performance potential (Figs. 4 and 5). The performance of the moveable sidewall concept was estimated by adding a calculated nozzle exit full sudden expansion (closed position) or contraction loss (open position) to predicted stage losses. Pivoted vane stage performance was generated from an in-house data base combined with an off-design computer code. The moveable sidewall concept showed a higher performance potential for the same leakage loss assessment (Fig. 6), and was the preferred configuration used in the remainder of the study. The gas generator turbine design point efficiency variation with cycle pressure ratio given in Fig. 7 is based on a combination of turbine specific speed relationships, a radial turbine efficiency prediction computer code, and an engine configuration study.[14] Performance is based on a thermodynamic efficiency defined as the ratio of actual turbine work to the sum of the isentropic works of the primary and cooling flow streams, each expanded from their respective inlet to fully mixed turbine exit conditions. A heat-transfer analysis was also conducted on the turbine, giving the cooling requirements and design point loss penalty breakdown shown in Table 2 and Fig. 8 for rotor inlet temperatures of 1644 K (2500°F) and 1477 K (2200°F), respectively.

Cycle Optimization Study

A design point parametric optimization was initially conducted at a 60% power rating, where most of the mission duty time is expended. Subsequent analysis showed that optimizing the turbine flowpath at 70-80% maximum flow resulted in a minimum mission fuel consumption. Figure 9 summarizes the design point performance of several configurations considered.[7] A free turbine turboshaft engine with an optimum compressor pressure ratio of 16:1 and a turbine inlet temperature of 1477 K (2200°F) were selected for further study. At this temperature only a limited amount of cooling is required, thereby lowering cost and complexities.

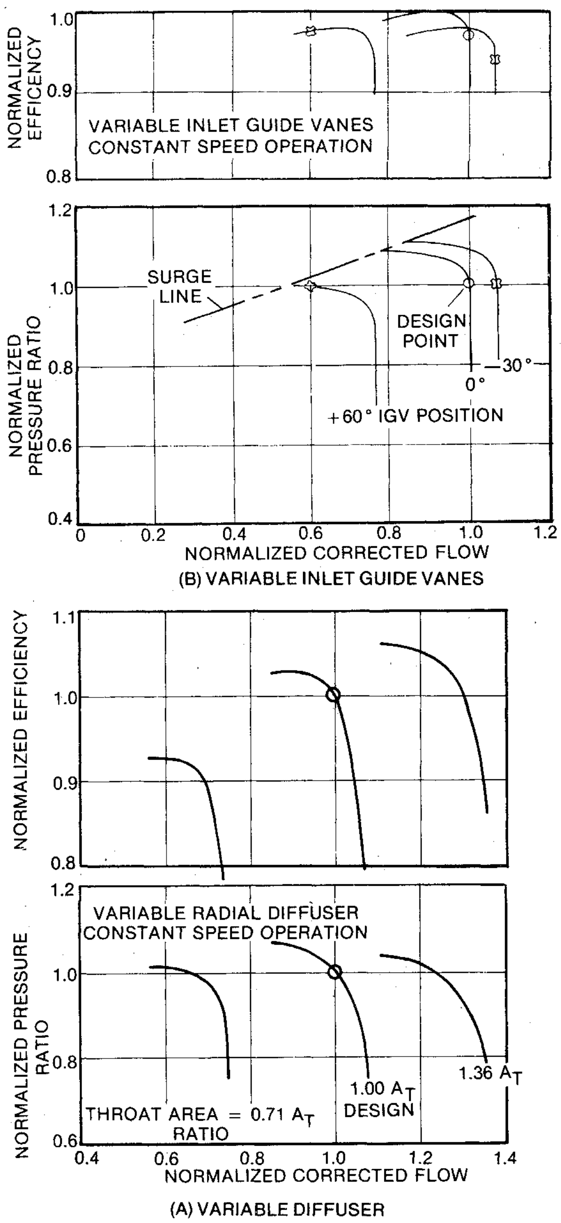


Fig. 2 Compressor range extension.

Engine Configuration/Performance

Figure 10 shows the engine and component configuration. The double centrifugal compressor uses backward curvature blading and provides a pressure ratio split of 7:1 and 2.29:1 to develop an overall pressure ratio of 16:1 at 78.3% efficiency, including losses for inlet guide vanes, diffuser vane endwall, and interstage duct losses. A rotative speed of 71,000 rpm results in reasonable specific speeds on both compressor stages ($N_s = 120$ and 84) and on the driving radial turbine ($N_s = 61$).

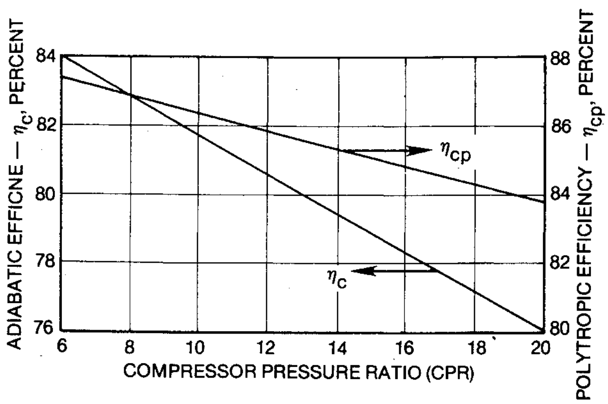


Fig. 3 Compressor design point efficiency change with compressor pressure ratio.

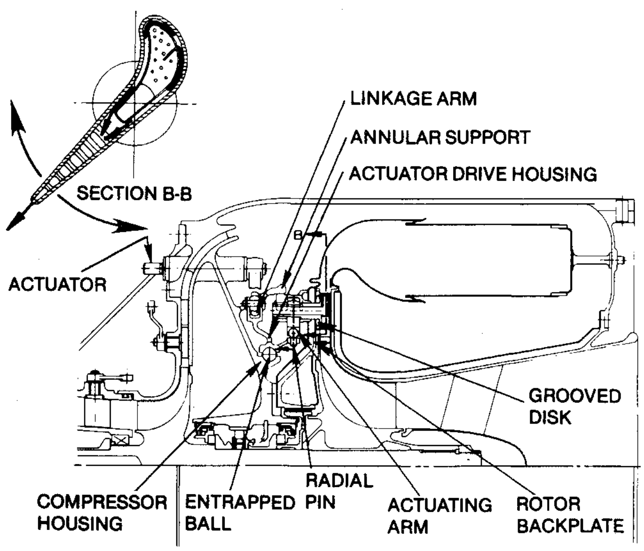


Fig. 4 Pivoted nozzle concept.

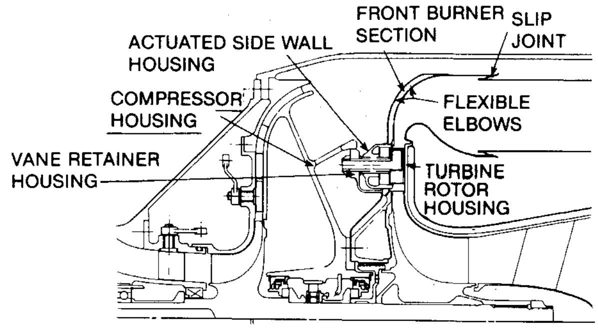


Fig. 5 Moveable sidewall concept.

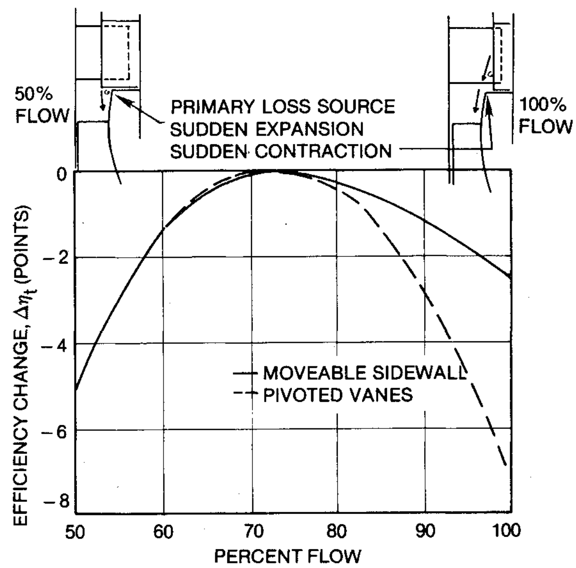


Fig. 6 Moveable sidewall off-design performance.

The uncooled 657-m/s (2155-ft/s) tip speed radial turbine rotor requires an advanced material such as a commercial rapid solidification (CRS) powder metal with directionally recrystallized (DR) blade tips to meet the 4000-h life.

Moveable sidewalls are used in tandem on the two compressor radial diffusers and the gas generator turbine. Variable inlet guide vanes are used on the compressor and power turbine. Only one master positioner moves all of the variable geometry to simplify controls.

The combustor was sized conservatively at the maximum flow conditions to maintain a reasonable pattern factor over the flow range required without the use of variable geometry.

Figure 11 shows the off-design characteristics of the VARICAP cycle compared to a simple cycle with a variable power turbine (SCVPT). A variable power turbine was assumed to show the simple cycle to its maximum advantage by matching the compressor operating line through peak efficiency at all speeds. In addition, the simple cycle gas generator was assumed to be free of variable geometry losses to provide higher efficiencies over most of the power spectrum (Table 3). Although component efficiency levels of the SCVPT cycle were higher than the VARICAP cycle, the SCVPT's lower thermal efficiency and poorer matching characteristics result in lower overall engine performance. The VARICAP mission duty cycle time-weighted fuel-consumption reduction was found to be 7% compared to the SCVPT.

Variable Geometry Turbine—Fabrication and Test

Two experimental programs were directed to providing a data base on the moveable sidewall, variable geometry radial turbine. Under the Variable Stator Radial Turbine (VSRT) program, NASA Contract NAS3-23163,[8,9] a research turbine with a known high-performance base was modified to permit testing with a moveable sidewall nozzle and combinations of nozzle exit fairing rings and rotor exit constriction rings. Testing was conducted on 31 different configurations over a flow range from 62 to 120% of design. Figure 12 shows some typical data obtained. The adiabatic efficiencies shown include leakage penalties that become more significant as flow is reduced at a fixed speed. An "L" seal, typical of an actual engine application, was used on the nozzle leakage gap. This seal showed the same performance as positive sealing, recovering 2.5 points in efficiency, data point "A" (Fig. 13) over a geometry that used a 0.4-mm (0.016-in.) gap around each of the nozzle vanes.

The Variable Area Fabrication and Test (VAFT) program, under NASA Contract NAS3-23173,[10] provides for the fabrication and aerodynamic test of the rotor designed under the Cooled Variable Nozzle Radial Turbine program.[7] This turbine, similar to the VSRT (Fig. 14), was fabricated at twice size so that the actual engine Reynolds numbers were duplicated in the test rig. Provision was also made to simulate cooling injection and leakages of the nozzle and turbine stage. The test plan also called for evaluation with individual hub and shroud nozzle sidewall actuation over a speed range from 60 to 100% and a flow range from 50 to 100% of maximum.

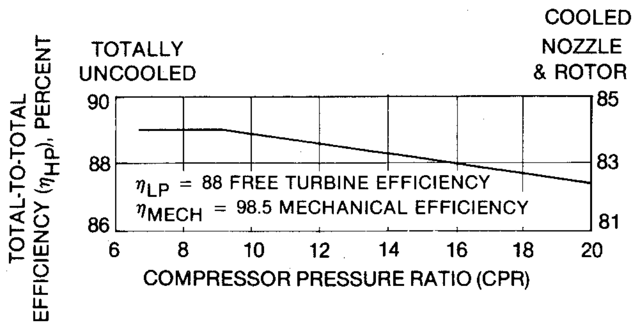


Fig. 7 Turbine design point efficiency change with compressor pressure ratio.

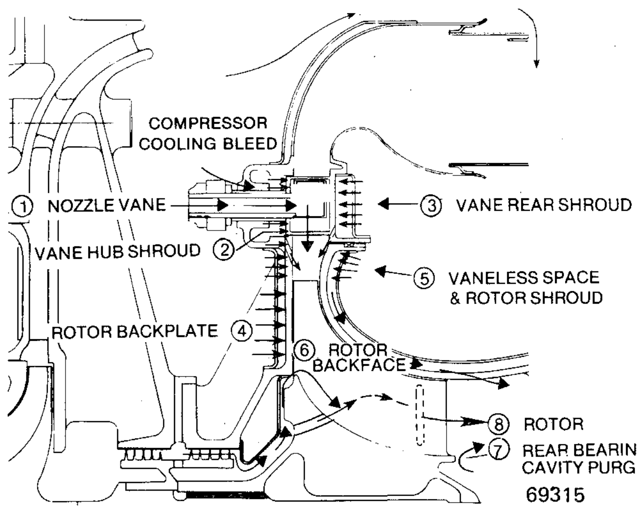


Fig. 8 Turbine cooling and leakage flows.

Figure 15 shows the total-to-total efficiency and flow of the turbine stage as a function of turbine pressure ratio and nozzle sidewall position. Measurements were made with an inline "Lebow" torquemeter and performance includes losses due to nozzle gap sidewall leakage past the L-seals. The performance, at design pressure ratio and above, was within 0.3 points (experimental accuracy) of data obtained with positive sidewall sealing (dashed curve), showing that the L-seal was effective in reducing losses.

Penalties due to the injection of cooling flow on the nozzle and rotor backface are shown in Fig. 16. In the design or flush

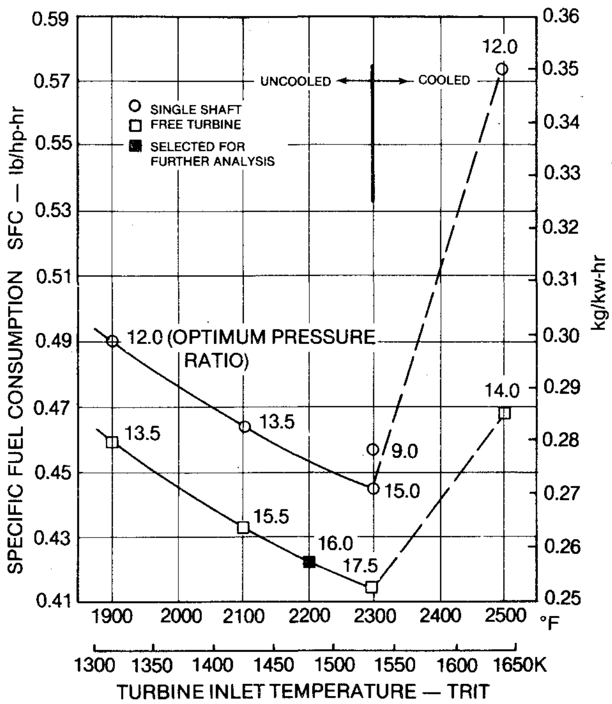


Fig. 9 Cycle optimization summary, 60% power design point.

Table 2 Cooling flows and performance penalties for cooled and uncooled turbine concepts

Cooling location (Fig. 8)	Component	Percent/efficiency change: 1644 K (2500°F) cooled rotor	Percent/efficiency change: 1477 K (2200 °F) uncooled rotor
1	Nozzle vane	4.3/0.4	3.0/0.3
2	Vane hub shroud	2.2/0.2	1.1/0.07
3	Vane rear shroud	2.4/0.3	1.1/0.1
4	Rotor backplate	1.1/0.1	0.9/0.03
5	Vaneless space and rotor shroud	0.9/0.1	0.4/0.1
6	Rotor backface and seal leakage	1.0/1.0	1.0/1.0
7	Rear bearing	0.3/0.3	0.1/0.1
8	Rotor	3.2/2.0	0/0
9	Rotor geometry penalty	0/0.6	0/0
	Total	15.4/5.0	7.1/1.7

Table 3 VARICAP and simple cycle component efficiencies

	Compressor		High pressure turbine		Low pressure turbine	
Power, %	VARICAP	SCVPT	VARICAP	SCVPT	VARICAP	SCVPT
50	78.3	81.3	84.9	88.2	88.0	88.0
80	78.3	80.0	88.0	88.7	88.0	85.7
100	76.4	80.0	86.4	89.0	88.0	82.1

wall position, no loss was measured up to 6% cooling, and performance improved slightly due to probable nozzle trailing-edge wake filling. At 50 and 100% wall positions, the efficiency loss was less than 2.0 points over the pressure ratio range tested.

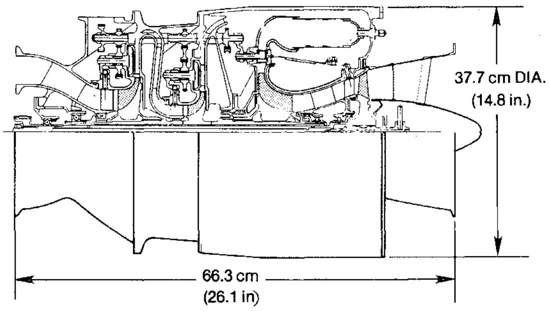
Variable Capacity Cycle Re-evaluation

The objective of a later cycle study was to verify that an updated VARICAP configuration (to late 1990s technology levels and including the preceding test data) could achieve or exceed the SFC improvement at 50-60% power.

The analysis was performed using the following source data:

1) The NNEP (Navy/NASA Engine Program) computer program.[15]

2) Variable geometry compressor maps synthesized from a combination of existing 90-deg unpublished test data on a radial compressor with an adjustable sidewall, Teledyne CAE backward-curved centrifugal test data with inlet guide vanes, and a loss model to account for the aero effects of the varia-



RATING — PERCENT MAX POWER	MAX	82	60
SHP — hp (kw)	916 (683)	755 (563)	540 (403)
SFC — lbs/hp-hr (kg/kw-hr)	0.43 (0.261)	0.41 (0.251)	0.42 (0.257)

Fig. 10 Engine configuration—four components controlled by one master positioner.

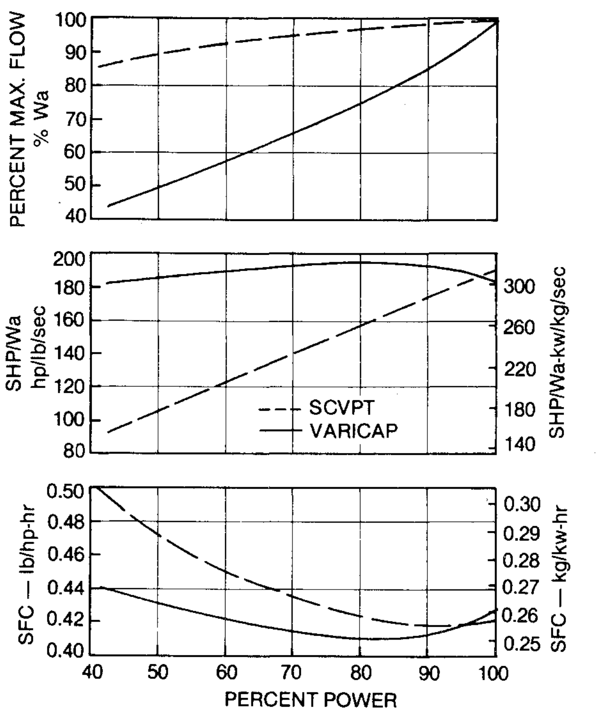


Fig. 11 VARICAP and SCVPT cycle performance comparison.

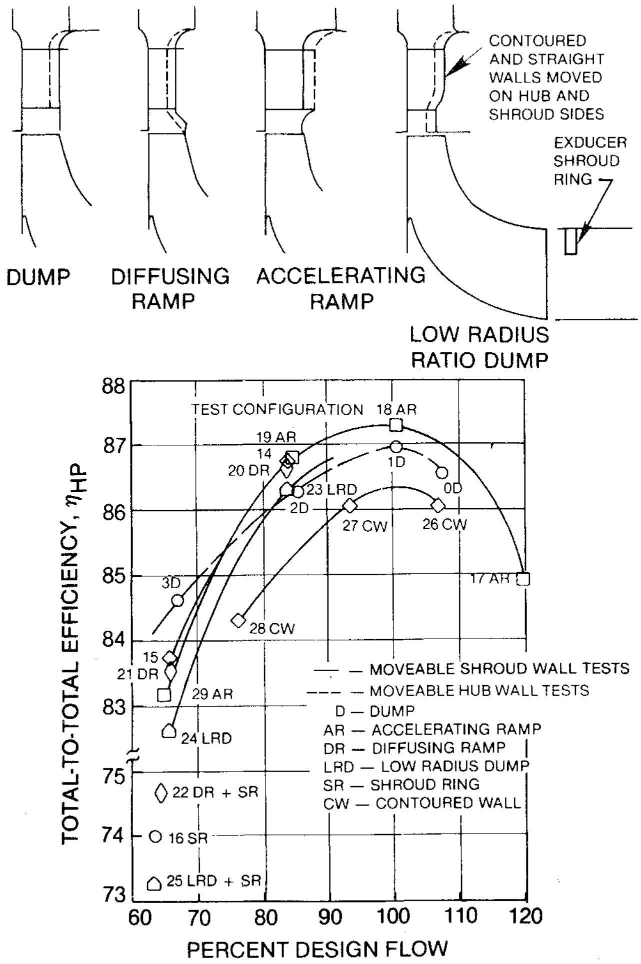


Fig. 12 Typical stage performance with shroud moveable sidewall geometries.

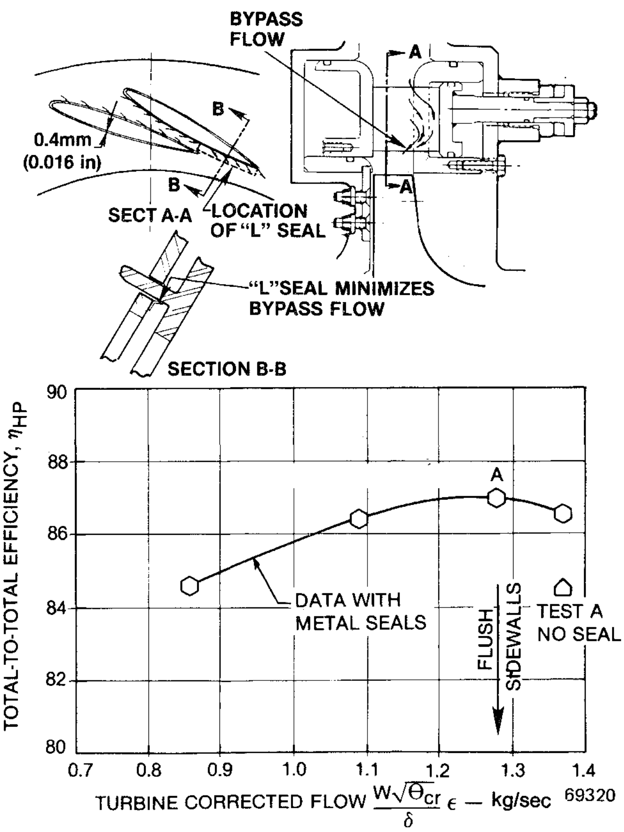


Fig. 13 Metal L-seals recover 2.5 points in performance.

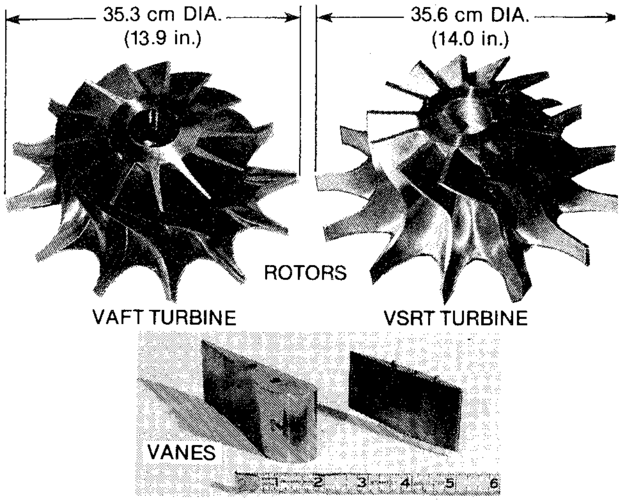


Fig. 14 Two turbines fabricated and tested with moveable sidewall nozzles.

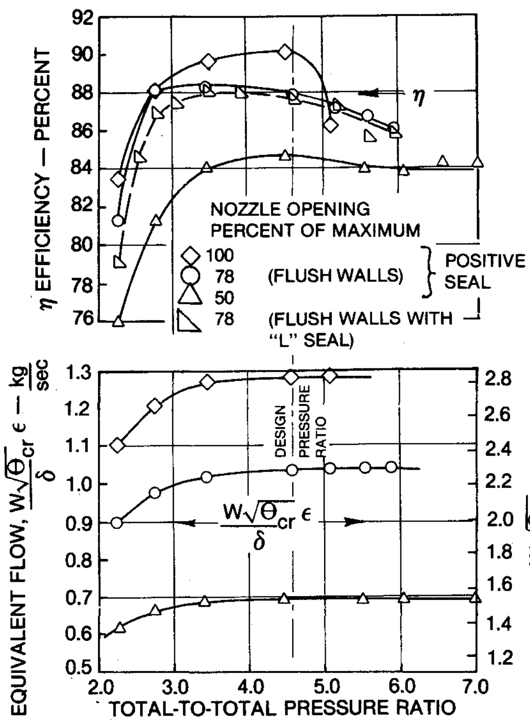


Fig. 15 Radial turbine stage performance with moveable sidewall nozzle.

tion of the sidewall geometry. All were applied to an advanced technology two-stage centrifugal compressor design at the original 16:1 pressure ratio.

3) The radial turbine map was adapted from the test data summarized in Figs. 15 and 16, and rated at 1477 K (2200°F).

4) The power turbine map was constructed from a combination of NASA and Teledyne CAE test results on variable geometry axial flow turbines.

Two approaches were used to run the performance calculations:

1) The original, i.e., constant rpm/constant pressure ratio (large geometry closures).

2) In anticipation of possible engine surge margin reduction, a 6.6% decrease of rpm was assumed at 30% power; this mode might be expected to make for lower geometry variations and better performance, as well as to increase surge/operating point range.

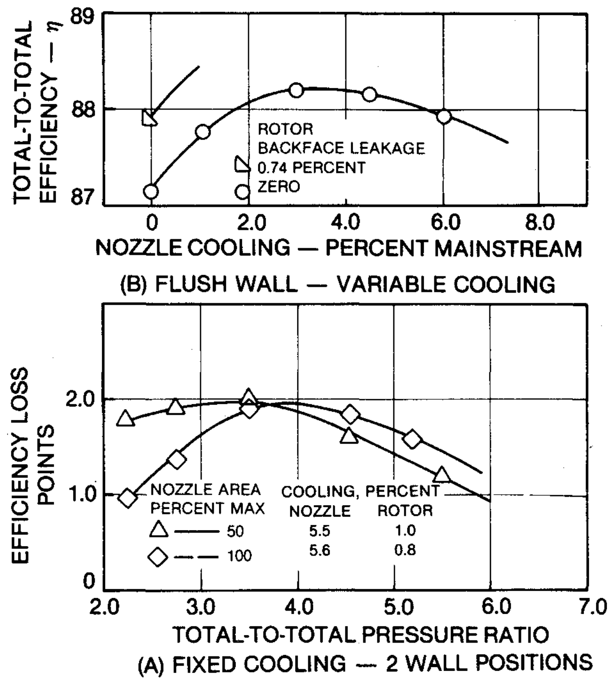


Fig. 16 Nozzle cooling and rotor backface leakage effects on turbine stage performance.

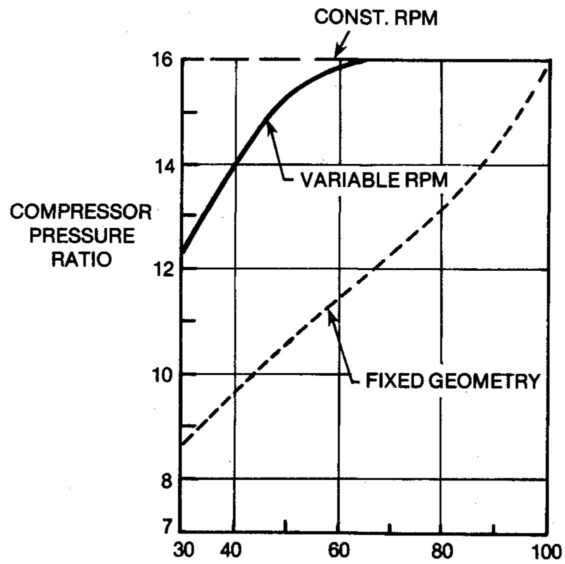


Fig. 17 Detailed component matching along the VARICAP operating line showing increased low-power pressure ratio in both constant and variable speed modes.

Figure 17 shows the operating line results of the analysis compared to a conventional fixed geometry engine; compressor pressure ratio is shown to be considerably above the conventional engine at any power below 100%, telegraphing the potential for reduced SFC. The test data of Ref. 16 corroborates many of the off-design assumptions made for the compressor prediction.

Figure 18 shows the variation of turbine inlet temperature with power, and indicates the increase available from the VARICAP concept [as limited by the low-pressure (LP) turbine limit load, see below]: at 50% power, the increase is approximately 130°F, again telegraphing the capability for improved SFC.

Figure 19 shows the required variable geometry setting changes on the high-pressure (HP) radial turbine and the con-

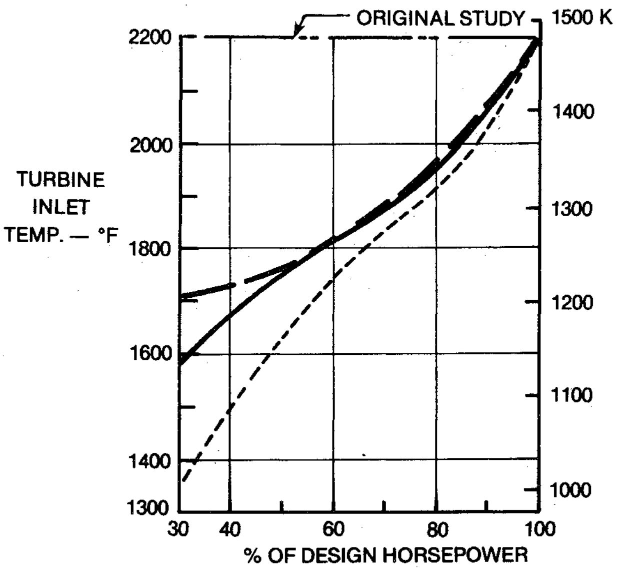


Fig. 18 Cycle analysis showing higher part power turbine inlet temperature, but not the original constant temperature assumption.

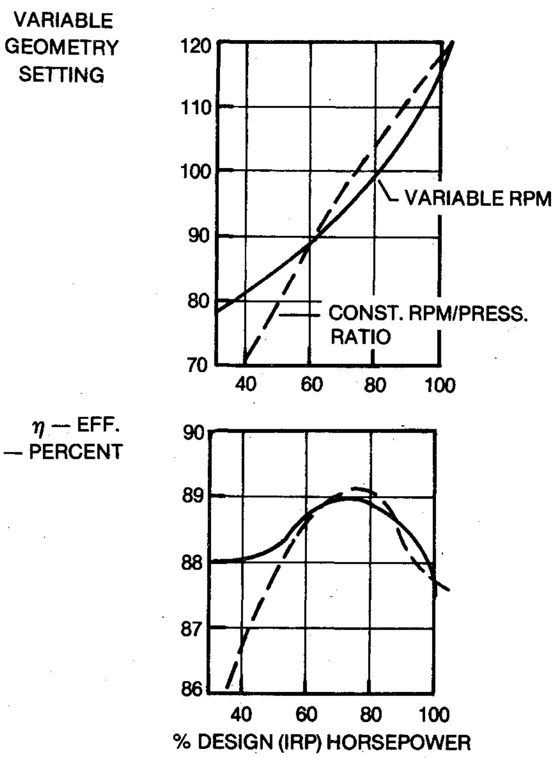


Fig. 19 60% power requires 30% geometry closure on the radial high pressure (HP) turbine.

sequent match efficiency. As expected, a higher range of geometry closure is required for the constant rpm mode, resulting in lower efficiency at part power. However, the end results showed insignificant differences of SFC vs power due to offsetting changes in the other components.

The results of this study are summarized in Fig. 20. The figure compares the characteristic shapes of typical 1990s engines, a "best" 1984 1000-hp engine of higher rated SFC (but similar curve shape), the preliminary, and most current estimates from the VARICAP cycle analysis. The 1990s projected conventional engine performance did not utilize the variable power turbine assumption of the earlier analysis. It was assembled from 10 current production engines; all were

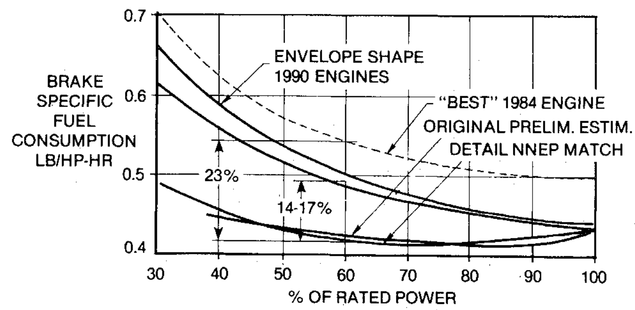


Fig. 20 Detail cycle analysis validating the SFC savings predicted in the initial study.

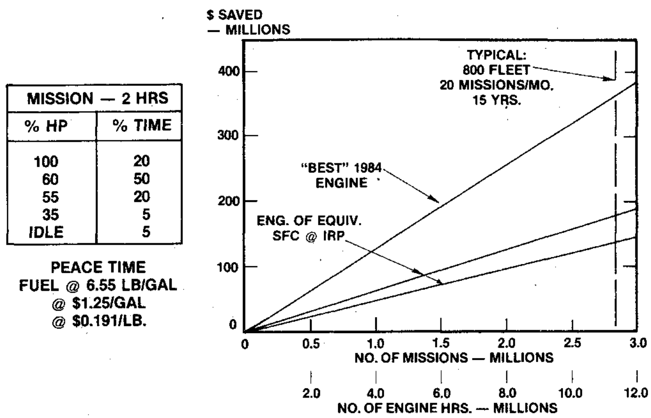


Fig. 21 Twin engine rotorcraft, wherein VARICAP life-cycle fuel cost is reduced $160-370 million compared to 1990s and current engines, respectively.

scaled to 0.43 SFC at 100% rated power under the assumption that advanced simple cycle engines in the 1000-hp class could achieve at least this same advanced rated performance level. All of the SFC vs power curves fit within a narrow band of SFC, about ± 2% from a mean line, with the characteristic upward slope at low power. The combination of advanced component technology level, an uncooled turbine, and the variable geometry effects provides a 23% savings compared to the best 1984 engine, and 14-17% compared to the 1990s engine, in the 60% power range. The savings in fuel consumption are thus validated at the low power settings.

Mission Payoff and Benefits

To quantify the benefits of the VARICAP cycle in typical rotorcraft operation, the 2-h mission described in the section entitled "Cycle—Configuration Studies" was used, along with an 800-vehicle, twin-engine fleet operating at 20 missions per month over a 15-yr life cycle. Fuel costs were estimated for peacetime operations at $1.25/gal and the fuel burn savings calculated as shown in Fig. 21. Projecting the savings to the life-cycle limit results in a $370 million lower cost for fuel compared to the 1984 best engine, and $160 million savings when compared to an advanced engine of equivalent SFC at intermediate rated power (IRP). The primary driver is the 70% of the mission requirement at 55-60% of IRP.

Additional potential benefits of the VARICAP cycle can also be projected. The updated cycle did not provide the desired constant turbine inlet temperature at part power; this was determined to be an artifact of the assumed single-stage LP turbine configuration. The power turbine matched at limit load as geometries were closed at 60% IRP, and an attempt was made to match for constant turbine inlet temperature. Inspection of the results pointed to an apparent additional potential (derived from parametric calculations) of about 7% reduction in SFC. This is in part an illusion, because the brake horsepower also increases with temperature, thus the match point will no longer be at the assumed 60% power setting. Nevertheless, an improved limit load level and matching of the variable geometry components can decrease the flow and achieve a part of the 7% reduction. The analysis did indicate the design direction to extract the best performance out of the cycle, and how to accomplish it with component matching and baseline geometry settings.

A second additional benefit could result from using the variable geometry to increase the available engine power in a one-engine-inoperative (OEI) emergency situation;[17] it remains for future analyses to evaluate how much power capability exists above IRP by opening the geometry and increasing flow and turbine inlet temperature. The life impact will be a function of the type of materials to be used in the 1990s and a tradeoff between stress rupture (high-temperature/high-speed operation) and low cycle fatigue (large temperature and speed changes) limits.

The final payoff parallels the OEI condition in projecting an improvement in 4000-ft/90°F takeoff capability. Engines are normally sized for this condition, but the VARICAP could result in a smaller size engine than a conventional configuration, thus lowering cost and fuel burn.

These additional payoffs will be evaluated in future growth appraisals of VARICAP capabilities.

Summary and Conclusions

Continuing study and research on variable geometry components have made available new data to re-examine the potential of the all-variable engine concept. Some of this work has been reviewed and a cycle comparison was shown to evaluate the merits relative to a 1990s advanced simple cycle engine. The most recent turbine test data available were also integrated into a VARICAP cycle study comparison with the best of today's turboshaft performance. Based on this study, the following conclusions have been made:

1) The VARICAP concept has been validated as a preliminary design by a combination of variable sidewall turbine test data and detail cycle analysis.

2) In a turboshaft application for rotorcraft, VARICAP will provide over 14% SFC reduction potential at 60% power.

3) Compared to an equal technology conventional 1990s simple cycle engine over a typical mission duty cycle, VARICAP will result in an 11-14% fuel burn reduction.

4) Compared to the best 1984 production engine in the 1000-hp class, it will provide a 25% fuel burn reduction.

5) Additional effort is required to: a) optimize the payoff analytically and b) to test-substantiate the component characteristics at the required geometry closures for the compressor and in a hot variable radial turbine stage rig.

6) An engine can be configured with only four components with one master positioner to move all of the variable geometry. Design and development challenges lie in: control response, durability, leakages, combustor flow tolerance, reliability, fail safety, clearances, and complexity/cost.

Acknowledgments

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