

Shaft Power Extraction and Waste Heat Rejection using a Three Stream Variable Cycle Engine

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ABSTRACT

Variable cycle engines offer the potential to operate a turbine engine more like a high-bypass turbofan during subsonic cruise and more like a turbojet or low-bypass turbofan for high-performance maneuvers or when supercruising. Variable geometry within the engine enables flow holding, allowing it to ingest the maximum amount of air that the inlet can capture even at reduced throttle settings. This approach reduces spillage drag compared to the conventional approach which cuts back engine airflow by reducing fan speed. To achieve the desired thrust, airflow is modulated between the core, inner bypass, and outer bypass. The air in the outer bypass duct, known as the 3rd stream, has been proposed as a heat sink for various engine and aircraft heat loads since it is at a comparatively low temperature, having only passed through the fan portion of the engine's compression system. The objective of this research was to further develop an understanding of the feasibility of extracting large amounts of transient shaft power from a variable cycle engine and rejecting the resultant waste heat into the 3rd stream bypass duct. The engine was found to be capable of providing the required shaft power and rejecting the waste heat to the 3rd stream, but the impact on engine performance is non-negligible. Transient pulses can significantly increase engine temperatures in certain cases, bringing into question the proper approach to modulating the cooled cooling air which is also cooled in the 3rd stream. Furthermore, the 3rd stream itself can become an unattractively hot sink at certain flight conditions.

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INTRODUCTION

Most modern military and commercial fixed-wing aircraft are powered by turbofan engines. Though there are alternatives such as turboshaft, turbojet, ramjet, and more exotic approaches like pulse detonation engines, turbofans generally outshine other options for aircraft traveling at high subsonic and low supersonic speeds. Among turbofans, there is a wide span from low-bypass ratio (BPR) turbofans (BPR near 0.25) to high BPR turbofans (BPR near 10). The BPR determines aspects of the engine such as noise, fuel efficiency, maximum speed, and outer diameter necessary to achieve a desired thrust.

Variable cycle engines (VCE) strive to blend the most desirable aspects of low and high BPR engines through the use of variable geometry within the engine. The VCE considered in this research makes use of a second, outer bypass stream in addition to the standard core bypass of a conventional turbofan. This outer bypass duct is referred to as the 3rd stream. The addition of the 3rd stream has the benefit of enabling thrust to vary for a fixed inlet mass flow simply

by modulating the airflow through different engine flow paths [1].

As aircraft move toward more electric architectures, the amount of shaft power takeoff required from the engine increases. For many commercial aircraft, this tends to be paired with a decrease in bleed air requirements, as more aspects of the cooling system are driven electrically rather than pneumatically [2]. However, for engines that push peak operating temperatures higher and higher, significant compressor bleed flow is required for cooling within the engine even as customer bleed air is being reduced in favor of electrical power extraction. Before looking at the impact of power extraction (bleed or shaft) on a VCE, it is prudent to survey the underlying concepts individually.

Overview of Variable Cycle Turbine Engines

Turbojet engines are known for high specific thrust, which makes them well suited for high speed supersonic flight, short distance takeoff, and highly responsive thrust control (e.g. for intercept or combat maneuvering). These



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benefits come at the expense of significant noise at takeoff, high exhaust gas temperatures, and poor fuel economy during subsonic cruise (using thrust specific fuel consumption, TSFC, as the metric). Turbofans, specifically high-bypass turbofans, achieve better fuel economy than turbojets at subsonic cruise speeds by accelerating a much larger mass of air to a comparatively lower velocity to produce the same thrust. Turbofans have additional benefits of lower exhaust gas temperatures and reduced noise, but come with the penalty of significantly larger inlet areas (and maximum diameter). The root causes for these apparent tradeoffs are evident from examining the contributing factors in overall engine cycle efficiency. Overall engine cycle efficiency is defined as the product of the propulsive efficiency (the ability to produce thrust power from kinetic energy on a rate basis) and the thermal efficiency (the ability to produce kinetic energy on a rate basis and/or mechanical shaft power from thermal energy input on a rate basis) [3]:

$$\eta_o = \eta_p \cdot \eta_{th} = \left(\frac{2V_0}{V_e + V_0} \right) \cdot \left(\frac{\frac{1}{2} \dot{m}_{o10} \cdot (V_e^2 - V_0^2)}{\dot{m}_f \cdot LHV} \right) = \frac{(\dot{m}_{o10} \cdot (V_e - V_0)) \cdot V_0}{\dot{m}_f \cdot LHV}$$

where η_o is the overall cycle efficiency, η_p is the propulsive efficiency, η_{th} is the thermal efficiency, V_0 is the aircraft velocity (equivalent to the air velocity coming to the engine from an engine-based coordinate system), V_e is the nozzle exhaust flow velocity, $\dot{m}_{o10}$ is the mass flow rate of air entering the engine, $\dot{m}_f$ is the mass flow rate of the fuel being consumed by the engine (primary burner plus afterburner), and LHV is the lower heating value of the fuel.

It would appear that increasing airflow, decreasing fuel flow, and increasing nozzle exit velocity are each beneficial to the overall cycle efficiency. However, these terms are not independent of one another. Taking a look at the propulsive and thermal efficiencies separately provides further insight. Minimizing the nozzle exhaust flow velocity will maximize the propulsive efficiency. This is the approach taken by a high-bypass turbofan—accelerate a large amount of air to a relatively low nozzle exit velocity. On the other hand, minimizing the nozzle exhaust flow velocity actually drives down the thermal efficiency. This apparent conflict between thermal efficiency and propulsive efficiency suggests that there is no good solution. However, there are observations that can still lead to an efficient design. The first is that a turbofan engine can have more than one nozzle (i.e. one nozzle with a high nozzle exhaust flow velocity and a second nozzle with a low one) and the second is that variable geometry within a variable cycle turbofan can enable it to behave either more like a low-bypass turbofan (high thermal efficiency) or more like a high-bypass turbofan (high propulsive efficiency), depending on the mission segment.

By taking advantage of both of these points, dual nozzles and internal variable geometry, a VCE can achieve the additional benefit of flow holding to reduce spillage drag. Spillage drag occurs when the engine's operating point requires that it swallow less air than the inlet is capable of

capturing. This extra air is spilled around the engine, creating drag. This concept is illustrated in Figure 1.

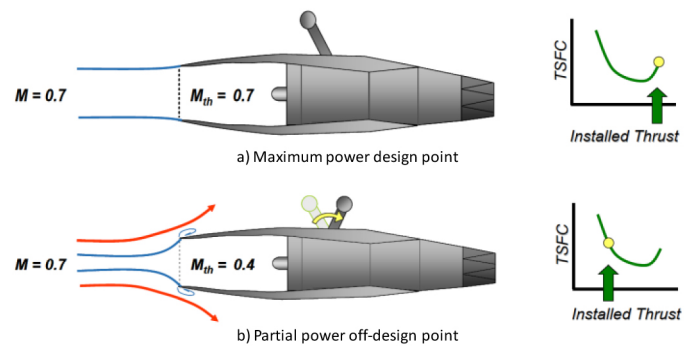


Figure 1. Spillage drag due to airflow mismatch [4]

In the upper view (Figure 1a), the engine is at its maximum power design point. In this case, the engine ingests all air captured by the inlet, creating very little spillage drag (note that there are, of course, other drag terms which remain). When a conventional turbofan is throttled back to a reduced power setting, the fan speed is normally reduced and therefore the engine requires less air. The air that is decelerated by the inlet but not consumed by the engine must go around the engine, creating spillage drag (Figure 1b). The magnitude of the spillage drag is governed by the mismatch between the inlet capture airflow and the airflow ingested by the engine, though the worst spillage drag may occur at intermediate supersonic Mach numbers (MN) where the product of the spillage drag coefficient and dynamic pressure is the largest [4].

The VCE enables flow holding to reduce the spillage drag. Flow holding is an approach whereby internal engine geometry is adjusted such that the engine's total airflow demand remains at the maximum that the inlet can provide despite a need for reduced thrust. To accomplish this, the corrected fan speed is maintained at 100% of the design value and the airflow is distributed between the engine's various flow paths to achieve the desired thrust. There is, however, a point where flow holding is no longer beneficial. When the turbomachinery variable geometry settings are pushed too far from their ideal positions in order to accomplish the flow modulation, the benefits of reduced spillage drag are outweighed by the reduced efficiencies of compressors and turbines [4].

Overview of Engine Power Extraction

The vast majority of the energy available on an aircraft resides in the fuel. The main engines are the primary consumers of the fuel, and are therefore responsible for supplying nearly all of the aircraft's power needs. For turbofans, a substantial portion of total engine power goes toward producing thrust (thrust power). The two other ways of producing power from the engine are through bleed air extraction and shaft power extraction. The latter tends to be subdivided into hydraulic power (pressurized flow from

shaft / gearbox driven pumps), mechanical power (shaft / gearbox driven devices such as fuel pumps) and electrical power (from shaft / gearbox driven generators).

High pressure bleed air has traditionally been an important aspect of aircraft engine design. Because any flow not available to produce thrust is a debit to TSFC, there is a desire to minimize bleed. However, using the compressors in the main aircraft engine generally is more economical than including separate hardware to create high pressure pneumatic power. The bleed air has traditionally been used for cabin pressurization, the environmental control system (air conditioning), ice protection, onboard inert gas/oxygen generation, and cooling of some avionics [5]. More recent aircraft programs have sought to reduce or eliminate the need for main engine bleed air and instead drive the majority of these items electrically. In a move toward a more electric aircraft, the electrical power extraction load would increase in exchange for reductions in hydraulic, mechanical, and pneumatic loads. In conventional aircraft, electrical power is required for cabin lighting, avionics, fans, etc. It has traditionally been on the order of a hundred kilowatts, but in a move toward a more electric aircraft architecture, it could easily exceed a megawatt [5].

In the study engine, there are three compressors and two shafts capable of power extraction. The customer bleed air requirements are set to a minimal (but non-zero) value in these studies. A base level of power extraction is taken from both the high-pressure (HP) and low-pressure (LP) spools, but the additional transient shaft power extraction is from the LP spool. LP shaft power extraction has been shown to have more available power, possible operability benefits, and a less detrimental impact on TSFC at some operating points—especially when combined with HP power extraction [6].

MODEL DEVELOPMENT

Engine Simulation Computational Framework

The Numerical Propulsion System Simulation (NPSS) is a computational framework/simulation environment developed by NASA under a cooperative effort with other government agencies, academia, and the propulsion industry. While it is a flexible framework that can be used to model many types of systems, the built-in thermodynamic tools make NPSS particularly well-suited for developing engine simulations. It is an object-oriented package, which fits well with the modular nature of engines [7]. Using the modeling tool itself consists of: 1) selecting a thermodynamic package; 2) defining and instantiating components; 3) linking components together; 4) configuring the solver; and 5) executing a simulation.

During the course of this work, it was determined that NPSS was not particularly well suited for modeling the engine plant's controller. For this reason, the thermodynamic cycle model was developed in NPSS, but position commands for variable geometry, fuel flows, etc. were passed into the model from an external source. As used in this work, the NPSS cycle model is controlled externally by Simulink. An additional factor in this decision is that future work will likely include integrating the study engine with additional Simulink models. The communication between NPSS and Simulink is facilitated by incorporating the NPSS model as an S-function within the Simulink model. A configuration file defines the NPSS parameters that are set by Simulink and the variables that are passed from NPSS back to Simulink. Though not the only viable approach, all data logging was done in Simulink (including NPSS cycle performance variables, which were passed out of the S-function).

Study Engine Model

Largely building upon published industry work, academia has conducted research into VCEs, including selective bleed engines. This engine is a two-spool afterburning turbofan with two low-spool driven compressors and one high-spool driven compressor. It is a three stream architecture, having two bypasses around the core. The outermost bypass stream discharges through a separate nozzle, while the inner bypass mixes with the core flow before being ejected through the primary convergent-divergent nozzle [8]. Later dubbed a double bypass engine, the selective bleed architecture is very similar to the one used in this research. The example double bypass engine shown in [Figure 2](#) was designed for two operating modes—a subsonic mode and a supersonic mode. This engine used variable geometry to effectively close off flow to either the inner bypass (subsonic mode) or to the outer bypass (supersonic mode) [9]. The cycle presented in this document used a more continuous operating mode, as it has the additional requirement that both the 2nd stream (inner bypass) and 3rd stream (outer bypass) maintain a minimum flow level.

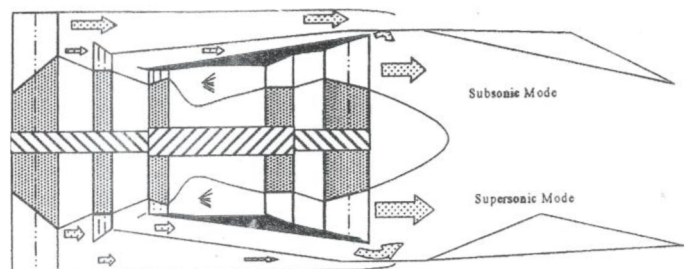


Figure 2. Double bypass engine [9]

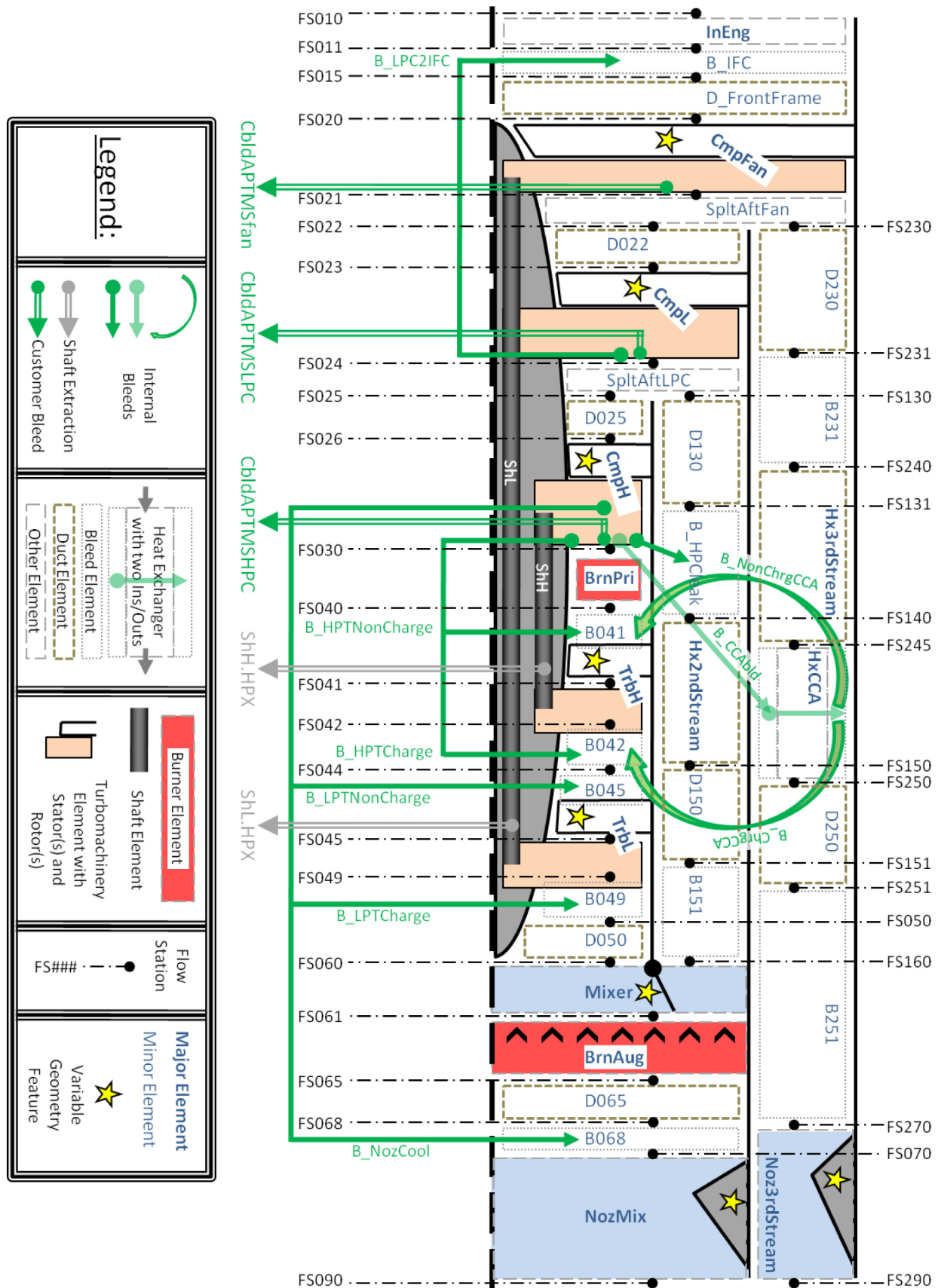


Figure 3. Study engine cycle schematic

Table 1. Flow station numbering and description

Station #	Location Description
0	Free stream (not shown in Figure 3)
010	Inlet entrance
011	Inlet element exit Inlet flow control bleed element entrance
015	Inlet flow control bleed element exit Front frame (duct element) entrance
020	Front frame (duct element) exit Fan entrance
021	Fan exit First splitter element entrance
	<i>(fan exit flow bypassed to the 3rd stream)</i>
230	First splitter element exit into the 3 rd stream duct Duct D230 element entrance
231	Duct D230 element exit Bleed B231 element entrance
240	Bleed B231 element exit 3 rd stream HX (external loads) entrance
245	3 rd stream HX (external loads) exit CCA HX entrance
250	CCA HX exit Duct D250 element entrance
251	Duct D250 element exit Bleed B251 element entrance
270	Bleed B251 element exit 3 rd stream nozzle entrance
280	3 rd stream nozzle throat (not shown in Figure 3)
290	3 rd stream nozzle exit
	<i>(fan exit flow continuing toward core)</i>
022	First splitter element exit continuing toward core Duct D022 element entrance
023	Duct D022 element exit LPC entrance
024	LPC exit Second splitter element entrance
	<i>(LPC exit flow bypassed to the 2nd stream)</i>
130	Second splitter element exit into 2 nd stream duct Duct D130 element entrance
131	Duct D130 element exit Bleed B_HPCleak element entrance
140	Bleed B_HPCleak element exit 2 nd stream HX (external loads) entrance
150	2 nd stream HX (external loads) exit Duct D150 element entrance
151	Duct D150 element exit Bleed B151 element entrance
160	Bleed B151 element exit Mixer bypass flow entrance
	<i>(LPC exit flow continuing toward core)</i>

Table 1 (Cont'd). Flow station numbering and description

Station #	Location Description
025	Second splitter element exit continuing toward core Duct D025 element entrance
026	Duct D025 element exit HPC entrance
030	HPC exit Primary combustor entrance
040	Primary combustor exit Bleed B041 element (for HPT non-chargeable cooling flow) entrance
041	Bleed B041 element (for HPT non-chargeable cooling flow) exit HPT (rotor) entrance
042	HPT (rotor) exit Bleed B042 element (for HPT chargeable cooling flow) entrance
044	Bleed B042 element (for HPT chargeable cooling flow) exit Bleed B045 element (for LPT non-chargeable cooling flow) entrance
045	Bleed B045 element (for LPT non-chargeable cooling flow) exit LPT (rotor) entrance
049	LPT (rotor) exit Bleed B049 element (for LPT chargeable cooling flow) entrance
050	Bleed B049 element (for LPT chargeable cooling flow) exit Duct D050 element entrance
060	Duct D050 element exit Mixer core flow entrance
	<i>(mixed flow)</i>
061	Mixer exit Afterburner entrance
065	Afterburner exit Duct D065 entrance
068	Duct D065 exit Primary (mixed flow) nozzle cooling bleed flow element entrance
070	Primary (mixed flow) nozzle cooling bleed flow element exit Primary (mixed flow) nozzle entrance
080	Primary (mixed flow) nozzle throat (not shown in Figure 3)
090	Primary (mixed flow) nozzle exit