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# A Study of Large-Scale Power Extraction and Insertion on Turbofan Performance and Stability

*Jeffryes W. Chapman*
*Glenn Research Center, Cleveland, Ohio*

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Glenn Research Center
Cleveland, Ohio 44135

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# A Study of Large-Scale Power Extraction and Insertion on Turbofan Performance and Stability

Jeffryes W. Chapman
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

## Abstract

This paper describes the effects of turbofan power extraction and insertion (augmentation) on engine performance and stability. The purpose of this paper is to present how power augmentation affects a dual spool gas turbine engine cycle where the engine will also be required to provide thrust. The goals for the paper are to describe effective limits of power augmentation and offer strategies, utilizing spool choice and variable geometries, to maximize augmentation effect. While Analysis is general, two potential uses are explored: Power extraction for electrified aircraft propulsion and power insertion for thrust assist. Results of the paper show it is possible to extract over 20 percent (at 85 percent max thrust) and gain roughly 12 percent of maximum thrust through power insertion.

## Nomenclature

| | |
|---|---|
| EAP | Electrified aircraft propulsion |
| HPC | High pressure compressor |
| HPT | High pressure turbine |
| HPX | Horsepower extraction |
| IGV | Inlet guide vane |
| LPC | Low pressure compressor |
| LPT | Low pressure turbine |
| OP | Operating |
| P | Pressure |
| PEGASUS | Parallel electric-gas architecture with synergistic utilization scheme |
| PSFC | Power specific fuel consumption |
| SFC | Specific fuel consumption |
| SLS | Sea level static conditions |
| STARC-ABL | Single-aisle turboelectric aircraft with an aft boundary-layer propulsor |
| T | Temperature |
| TEEM | Turbine electrified energy management |
| UTRC | United technologies research center |
| VACN | Variable area core nozzle |
| VAFN | Variable area fan nozzle |
| VBV | Variable bleed valve |
| VPF | Variable pitch fan |
| VSV | Variable stator vane |

**Subscripts**

| | |
|---|---|
| 2 | Station number for LPC inlet |
| 25 | Station number for HPC inlet |
| 3 | Station number for burner inlet |
| 4 | Station number for turbine inlet |

## 1.0 Introduction

Power extraction and insertion (augmentation) for a gas turbine engine can be defined as the addition or subtraction of power as offtakes. In a gas turbine engine, power is generated as air moves through the turbines. This power takes the form of torque on the turbine shaft and can be used to run the turbomachinery (fans and compressors), engine subsystems through the accessory gearbox (pumps, hydraulics, or engine cranking for starting), or to generate electricity via a generator. Power augmentation refers to any power added or removed from an engine shaft that is not used to power the engine's compression system. Note, power removed via bleed air may also be thought of as power extraction but will not be considered for this paper. This paper explores power augmentation and evaluates its effect on performance and stability, lays out a strategy for maximum power extraction capability or for maximum thrust assist, and details how negative effects of power augmentation can be mitigated. The described studies will consider a high bypass dual spool turbofan engine, with power augmentation applied to either the high pressure or low-pressure spool. Turboshaft engines that utilize a power turbine, where full power extraction would be expected, will not be considered.

Power augmentation on a gas turbine engine is not a new concept. Historically, power extraction has been used to run aircraft electrical systems or other aircraft systems and has traditionally consumed roughly 5 percent of fuel burned (Ref. 1). Power insertion has been used to crank the engine for starting purposes. These power off-takes may utilize a small percentage of turbine power at low altitudes, but at high altitudes they can represent a lager fraction as turbine power generation drops (Ref. 2). Newer aircraft concepts, specifically electrified aircraft propulsion (EAP) (Refs. 3 and 4) and high energy military concepts, (Ref. 5) have pushed the requirements for power augmentation. Concept vehicles, the Single-Aisle Turboelectric Commercial Transport with an Aft Boundary Layer Propulsor (STARC-ABL) (Ref. 6) and the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) (Ref. 7) (Figure 1), developed by NASA, demonstrate the need to understand the effects of power augmentation. In the STARC-ABL concept, two turbofans generate electrical power that is subsequently used to run a fan located at the tail of the aircraft. This fan is designed to run at a constant 1942 HP (1.4 MW), which relates to roughly 8 and 28 percent power extraction at takeoff and top of climb, respectively. In the PEGASUS, two wing tip mounted turboprops are used as range extenders for a mostly electric vehicle. Power insertion on the low-pressure shaft (LPS) of these turboprops is then used to boost fan thrust. Additionally, a single-aisle class aircraft concept was put forth by United Technologies Research Center (UTRC) where battery power would be used to assist conventional turbofans during

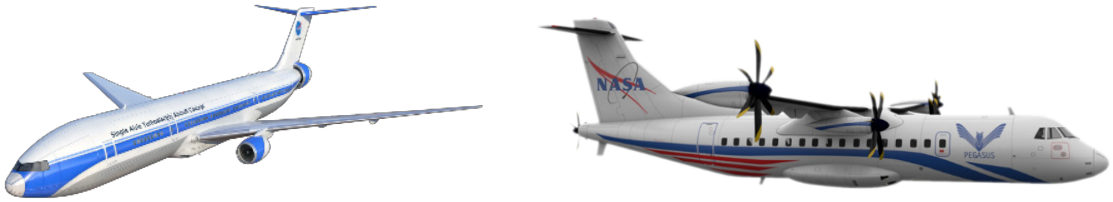

Figure 1.—STARC-ABL (left) and PEGASUS (right).

take-off with the battery shut off during cruise (Ref. 8). In the UTRC concept, it was found that power boost allowed for a reduction in vehicle engine size/weight resulting in a 3.4 percent overall system level fuel burn reduction.

There are many system level challenges to power augmentation. Compressors and turbines are design to operate at specific speeds and loads, and when turbine power is augmented, component operating (OP) points will shift. This shifting can lead to reductions in component performance, stall margin, and overall system efficiency. Previous studies have shown that, given a constant fuel flow, shaft speed will decrease for a shaft when power extraction is applied (Ref. 9). Stall margin will also decrease for the low-pressure compressor (LPC) when power is extracted from the high pressure turbine (HPT) (Ref. 10). These studies give a good overview of power extraction, however power insertion and the potential for mitigation of power augmentation effects is not addressed. This lack of literature on the subject demonstrates the need to research smarter extraction methods.

The objective of this paper is to perform a thorough operability and performance analysis of power extraction and insertion and layout general guidelines for obtaining the maximum power augmentation with the minimum negative effects. Although this analysis is intended to be general, three power augmentation applications will be reviewed, maximum power extraction, maximum power extraction at constant a constant thrust, and power insertion for thrust assist. For this study, a 20,000 lbf thrust dual spool turbofan simulation is constructed and power augmentation is studied for each spool individually and in combination. In these studies, engine variable geometries are either assumed to be on schedule, as developed for the default engine, or held constant. Operating envelopes are developed to define the location of maximum power augmentation. Additionally, variable geometry effects are examined and analyzed for mitigating the effects of power augmentation. The variable geometries considered are high pressure compressor (HPC) variable stator vanes (VSV), LPC inlet guide vanes (IGV), variable pitch fan (VPF), a variable bleed valve (VBV) between the LPC and HPC, IGVs on the turbines, a variable area fan nozzle (VAFN), and a variable area core nozzle (VACN). It should be noted that transient effects of power augmentation will not be studied here. Previous studies by NASA in turbine electrified energy management (TEEM) have shown how using power transfer between spools can increase operability margins, enable reduced roles for or complete elimination of variable geometries, and enable ultra-low idle operation (Refs. 11 to 13). Therefore, this study will focus primarily on high power performance trends and steady-state stability.

Subsequent sections of this paper detail the sensitivity study and suggest management strategy. Specifically, a detailed description of the engine simulation is given in Section 2.0, followed by a power augmentation sensitivity study in Section 3.0. An analysis of power augmentation operational envelopes is given in Section 4.0. In Section 5.0 a discussion of the usefulness of variable geometries is detailed. Finally, summary and conclusions are given in Section 6.0.

## 2.0 Turbofan Simulation Description

The studies run for this paper consider a dual spool turbofan engine simulation. This simulation was developed in the numerical propulsion system simulation (NPSS) (Ref. 14) with architecture shown in Figure 2. In the simulation, the fan represents the fan tip and the LPC represents the fan hub along with the engine's booster. The fan, LPC, and the low-pressure turbine (LPT) are connected via a low-pressure shaft. The core of the engine consists of a HPC, burner, and HPT with cooling flow running from the HPC to the HPT, LPT, and to a hypothetical customer. The HPC and HPT are connected via a high-pressure shaft (HPS). A VBV is positioned to allow air to flow from station 25 to the bypass. Two nozzles (VAFN and VACN) are connected to the Fan bypass and LPT, respectively.

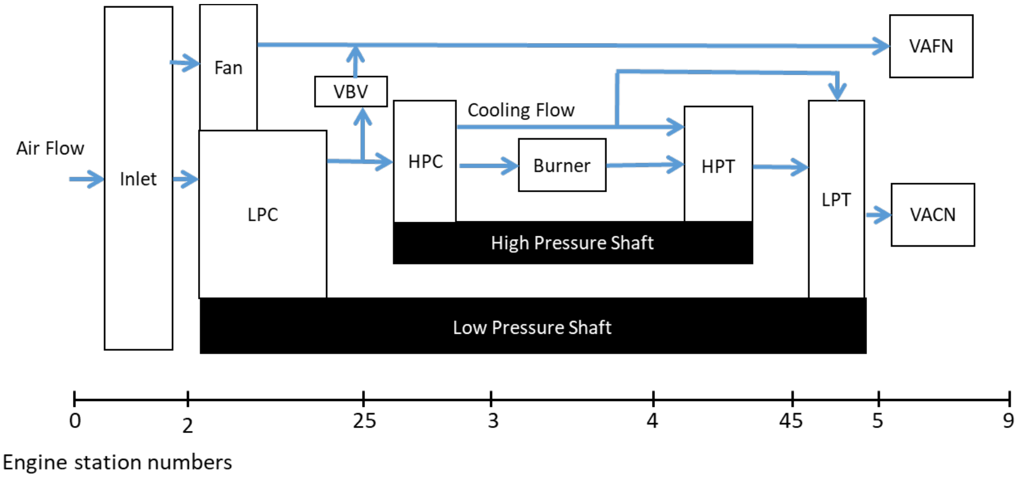

Figure 2.—Turboshaft NPSS engine simulation.

TABLE 1.—TURBOFAN ENGINE DESIGN POINT

| Environmental condition | Mach number | Altitude | Delta temperature, °R |
|---|---|---|---|
| | 0.0 | 0.0 | 0.0 |
| Flow | Inlet flow (lbm/s) | Bypass ratio | FAR |
| | 533 | 5.6 | 0.03 |
| Pressure ratios | Fan pressure ratio | LPC pressure ratio | HPC pressure ratio |
| | 1.7 | 2 | 23 |
| Performance | Thrust (lbf) | $T_4$ (R) | |
| | 18920 | 3330 | |
| Shaft speed | Low Pressure Shaft Speed (rpm) | High Pressure Shaft Speed (rpm) | |
| | 6032 | 19680 | |
| Design power extraction | High Pressure Shaft extraction (HP) | High Pressure Shaft extraction (HP) | |
| | 250 | 0.0 | |

When selecting an engine design point for this study it was determined to put forth a design that is not developed for large scale power extraction. As a result, the studies within this paper show how an “off the shelf” turbofan would respond when applied to a high-power augmentation application. It should be noted that any amount of power extraction could be taken into account during the design and this new design point would act as a starting point for unplanned power augmentation. While this would change the overall amount of possible power augmentation, it would not change the trends discussed in this paper.

The engine was sized to represent a 20,000 lbf class engine, with design criteria detailed in Table 1. During the design, inlet air flow and the fuel to air ratio (FAR) are set to obtain 18920 lbf thrust and a temperature of 3330 °R was selected for the turbine inlet temperature ($T_4$) limit. Additionally, the VBV is closed and VAFN and VACN positions are set to constants. Data for the design were gathered from public sources (Refs. 15 to 17) and component performance maps are generic with scaling applied to meet the design point. The power extraction design point is set to 250 HP for the high-pressure shaft and 0.0 HP for the low-pressure shaft, to represent a modest customer demand.

## 3.0 Turbofan Performance With Power Augmentation

With the characteristic turbofan model defined, performance simulations were run with varying power augmentation. To generate trends, high pressure or low-pressure spool auxiliary power was added or removed systematically, as shown in Figure 3. Power is adjusted to each spool exclusively, so when adding or removing power from the high pressure spool the low-pressure spool power augmentation was kept at its design point. Traces are generated at the sea level static condition (SLS) restricting $T_4$ to the design point. This study is run to demonstrate potential operating points that may be utilized while observing a maximum operating temperature. It is important to note that these points do not generate the same thrust and a high-power extraction application would need to account for the reduced maximum thrust.

Looking at the fan map in Figure 3, HPS and LPS power extraction both reduce fan speed and fan stall margin, while HPS and LPS power insertion increase fan speed. These trends occur because the engine is impeded by removing power, which reduces fan speed. Conversely, when power is added, the engine runs at higher power level and fan speed increases. It can also be seen that the change in fan speed due to HPS insertion is fairly low compared with the other power augmentations. LPC performance is more complicated and relies heavily on coupling with the HPC. With LPS extraction, LPC stall margin and pressure ratio are increased as the spool is impeded. With HPS extraction a large amount of LPC stall margin is lost as the HPC is impeded and draws less air from the back of the LPC. A similar effect can be seen with LPS power insertion. As power is added to the LPS, LPC pressure ratio increases. If power is added to the HPS, LPC pressure ratio drops as HPC speed increases and more air is pulled from the back of the LPC. Looking at the HPC map, it can be seen that HPS extraction and LPS insertion both slow the HPS, and HPS insertion and LPS extraction increase the speed of the HPS. In the speed reduction case, the HPS extraction impedes both spools causing corrected speeds to drop. For LPS power insertion, recall the increase in LPS speed. As the LPC speed increases, mass flow and HPC inlet pressure ($P_{25}$) also increase. Processing the larger amounts of mass flow at a higher pressure, impedes the HPC causing the HPS to slow. It is important to note that, although absolute mass flow is higher within the HPC, corrected mass flow is lower (due to higher pressures).

As mentioned above, engine performance is affected by power augmentation. In studying these performance changes, engine thrust, and fuel efficiency should be considered. For a typical engine, fuel efficiency is measured using specific fuel consumption (SFC) versus thrust or power, however the metric becomes difficult to interpret when the engine produces a substantial and changing amount of both.

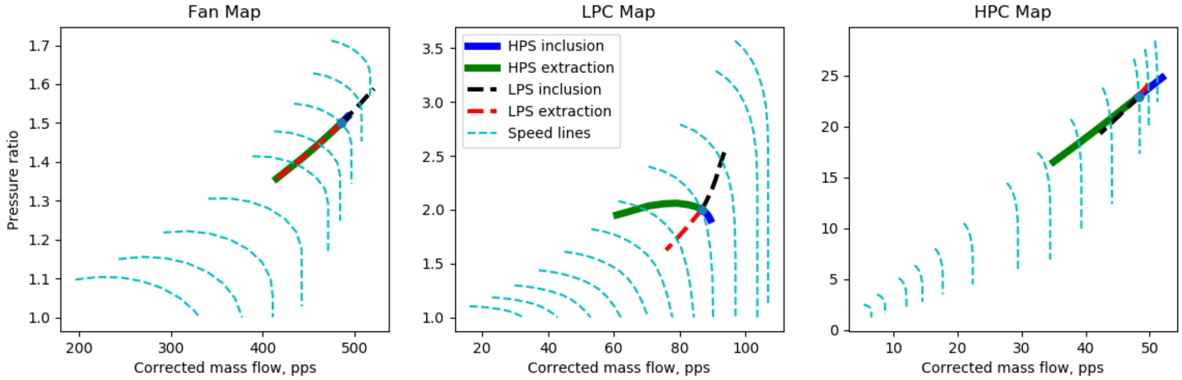

Figure 3.—Compressor maps with power extraction and insertion for the low- and high-pressure spools at SLS max power (constant $T_4$).

Research into new metrics show the potential to determine power production efficiencies, (Ref. 9) however these do not take into account propulsion generation. It is surmised that gaining an understanding of overall propulsion system efficiency requires an end to end model that includes electrical system and electrically driven populsors that determines total system thrust. This type of analysis is beyond the scope for this paper, where the engine is being analyzed independently from the full propulsion system, therefore engine fuel efficiency will be examined through turbine inlet temperature and total fuel flow.

The engine system was simulated with power augmentation (horsepower extraction (HPX)) on the LPS and HPS between –3000 and 3000 HP, (where negative power equates to power insertion) and holding $T_4$ constant. Turbine inlet temperature and fuel flow along with engine thrust and power extraction are shown in Figure 4. Engine thrust increases with power insertion and is reduced with power extraction. The flattening of the thrust around 22000 lbf and at high LP power insertion/HP power insertion is created when fan spool speed limit is reached. Similarly, at high LPS power extraction/HPS power insertion the HPC speed limit is reached and a subsequent increase in thrust reduction rate can be observed. The flattening of the thrust curve with LPS power insertion and HP power extraction is caused by an LPC stall margin limit. Turbine inlet temperature is held fairly constant during nominal operation, however, falls off when the two mentioned speed limits are hit. In the case where the LPC stall margin is hit, turbine inlet temperature rises as fuel flow is increased to the engine, driving the HPC faster, which reduces the LPC pressure ratio. This increase in fuel flow also drives up the turbine inlet temperature. Traces of fuel flow response generally mirrors the thrust level, with a larger roll off as power insertion is applied. Power extraction percent (Power augmentation/LPT power production) increases nonlinearly with increasing power extraction. This response is a function of the reduced LPT power generation resulting from the power extraction and reflected in the loss of thrust and fuel flow.

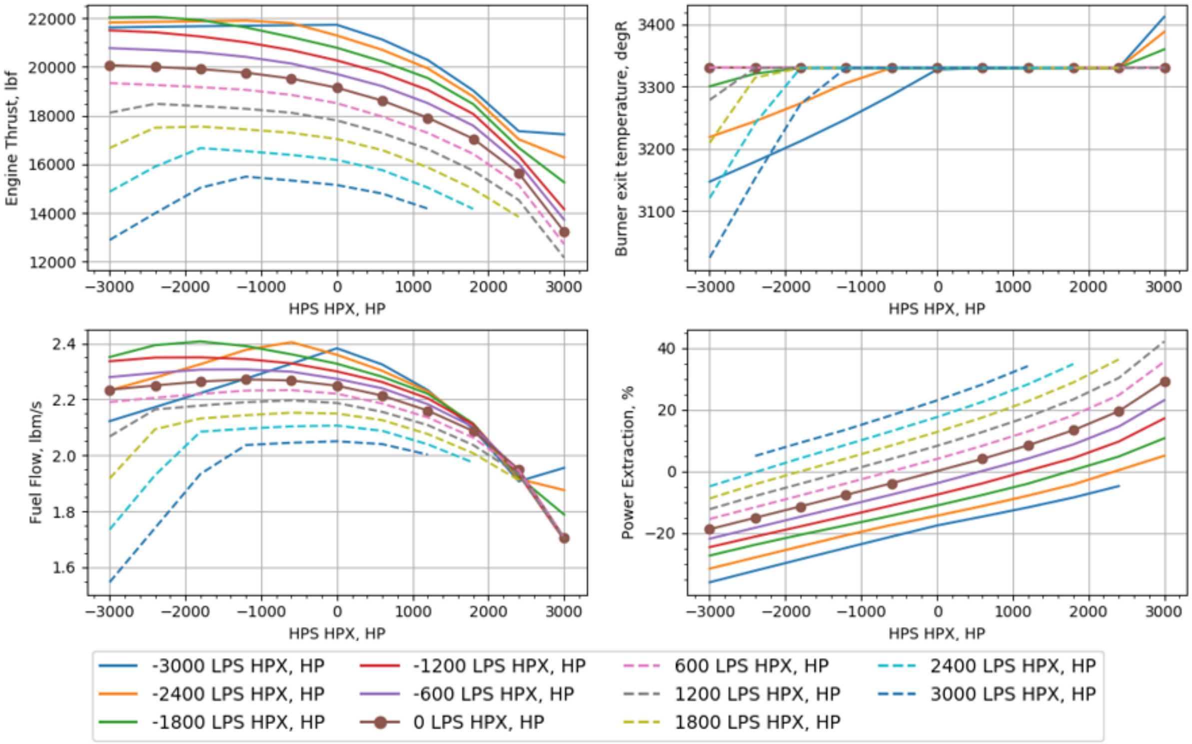

Figure 4.—Engine performance metrics with power extraction and insertion for the low- and high-pressure spools at SLS max power (constant $T_4$)

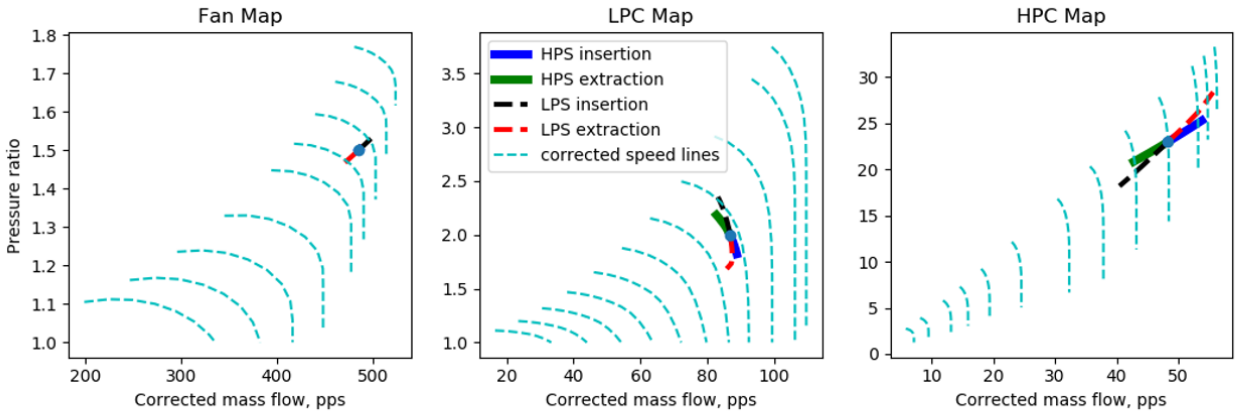

Figure 5.—Compressor maps with power extraction and insertion for the low- and high-pressure spools at SLS design thrust.

The above analysis was repeated considering a constant thrust demand. In this case, $T_4$ is allowed to increase to maintain thrust levels. A high-pressure compressor speed limit was also set to enable point convergence. Performance map trends for these simulations are shown in Figure 5. In this case, it can be observed that the fan operational point shifts very little. This lack of movement is due to the constant thrust demand and the fact that the majority of thrust comes from bypass air. For the LPC, pressure ratio increases and mass flow decrease with HPS extraction and LPS insertion. Conversely, pressure ratio decreases and mass flow rises slightly with HPS insertion, and initially mass flow stays roughly the same with LPS extraction. With high levels of LPS extraction the high-pressure compressor speed limit is hit, and mass flow begins to fall. The performance and operability trends are similar to the constant $T_4$ case with the exception that speeds and mass flow response are dampened. This dampening occurs because the engine fuel flow is being changed to maintain thrust, which allows the engine to increase or decrease speed to maintain mass flow rates. For the HPC, shaft speed, corrected mass flow, and pressure ratio are reduced with HPS extraction or LPS insertion. Conversely, shaft speed, corrected mass flow, and pressure ratio increase with HPS insertion or LPS extraction. Remembering absolute mass flow changes little within the LPC, therefore this is also true for the downstream HPC. The shifting HPC corrected mass flow can be directly related to the changes in $P_{25}$ and $T_{25}$ caused by the shifting pressure ratio of the LPC. Additionally, it can also be observed that power insertion (HPS or LPS) results in an increase in HPC stall margin.

The engine system was then simulated with a range of power augmentations (horsepower extraction (HPX)) for the LPS and HPS between –3000 and 3000 HP, while holding thrust demand constant, as shown in Figure 6. In this case, thrust is fairly constant at 19000 lbf, however at high LPS extraction the HPC speed limit is hit and thrust begins to roll off. Turbine inlet temperature increases as power extraction is increased. This rise in temperature is greater with LPS extraction than HPS extraction. Fuel flow response generally follows the turbine inlet temperature response; however, fuel flow is more linear due to changes in engine core flow that affect the turbine inlet temperature. It should also be noted that fuel flow at a given turbine inlet temperature is also affected by the compressor efficiency values that correlate to off nominal compressor operation, as shown in Figure 7. These efficiency losses are largely due to changes in LPS to HPS power extraction ratio and are generally higher with HPS power extraction. Power extraction percent increases linearly with 3000 HP correlating roughly with 20 percent power extraction regardless of which shaft the power is being take from.

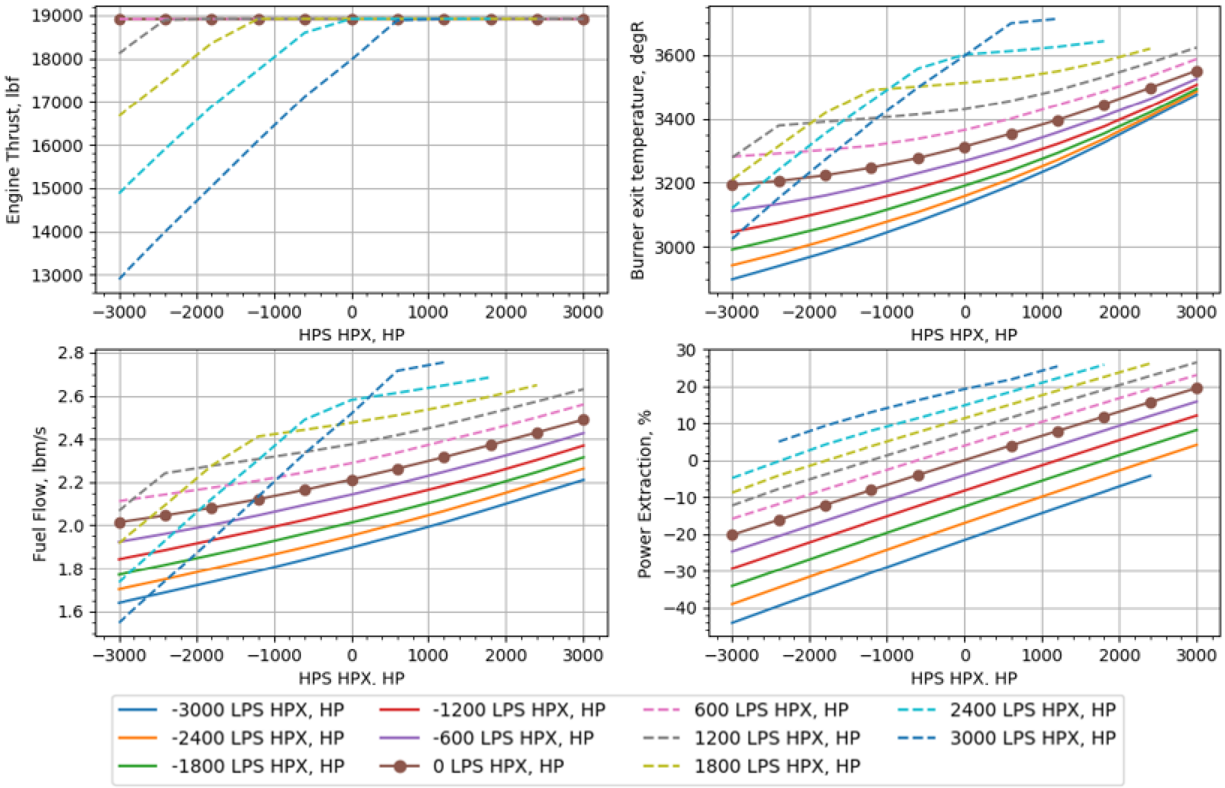

Figure 6.—Engine performance metrics with power extraction and insertion for the low- and high-pressure spools at SLS constant thrust.

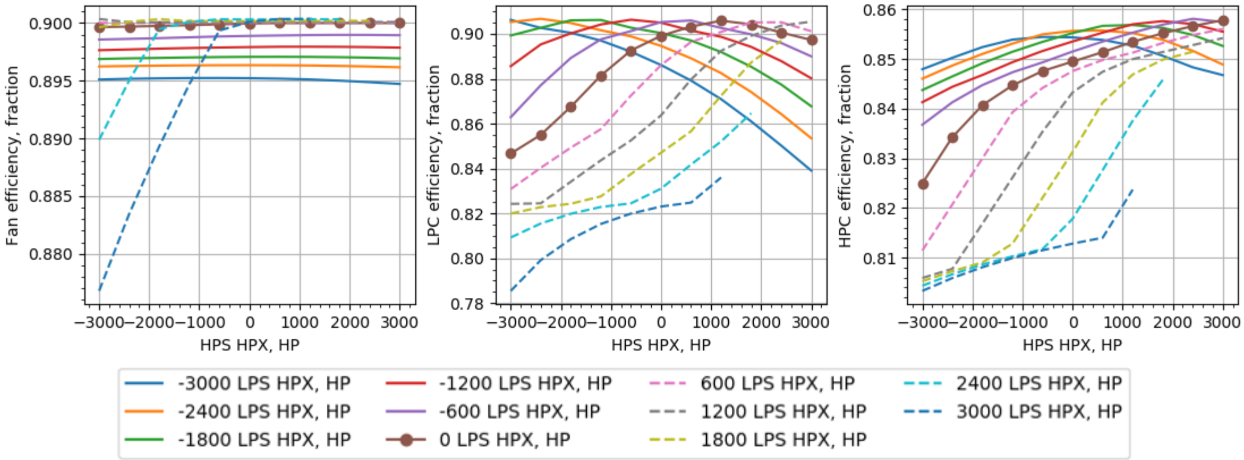

Figure 7.—Compressor efficiencies with power extraction and insertion for the low- and high-pressure spools at SLS constant thrust.

Once the SLS simulations were completed a similar simulation was performed at cruise, 35000 ft and 0.8 MN, as shown in Figure 8. Holding thrust to a constant 80 percent of max power, HPS and LPS were adjusted from –1000 to 1000 HP. Comparing the results with the SLS thrust constant case the results are similar, with changes in magnitude and starting central position. Engine performance trends are also the same with the exception of the power extraction trends, which contain lower amounts of total power extraction, however similar percentages are achieved, as shown in Figure 9.

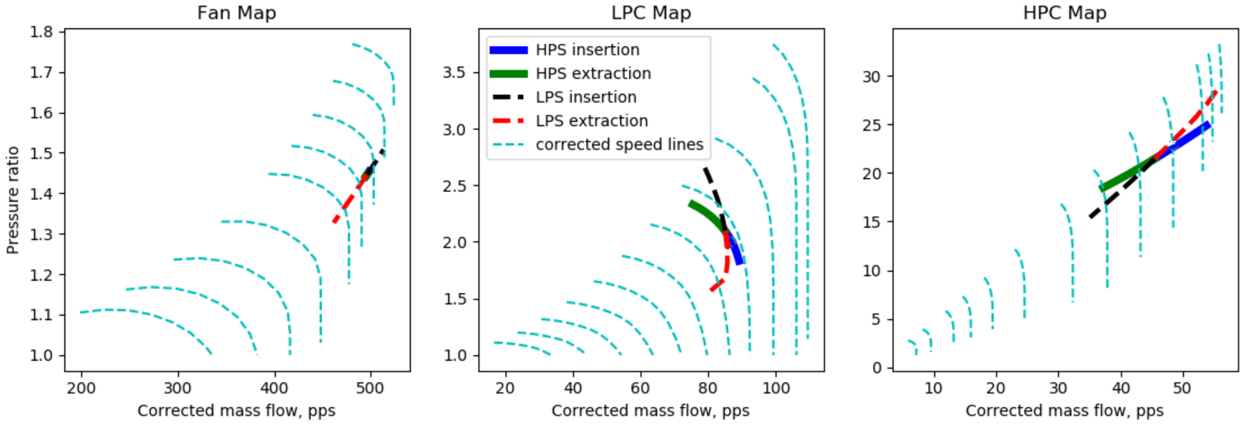

Figure 8.—Compressor maps with power extraction and insertion for the low- and high-pressure spools at cruise with constant thrust.

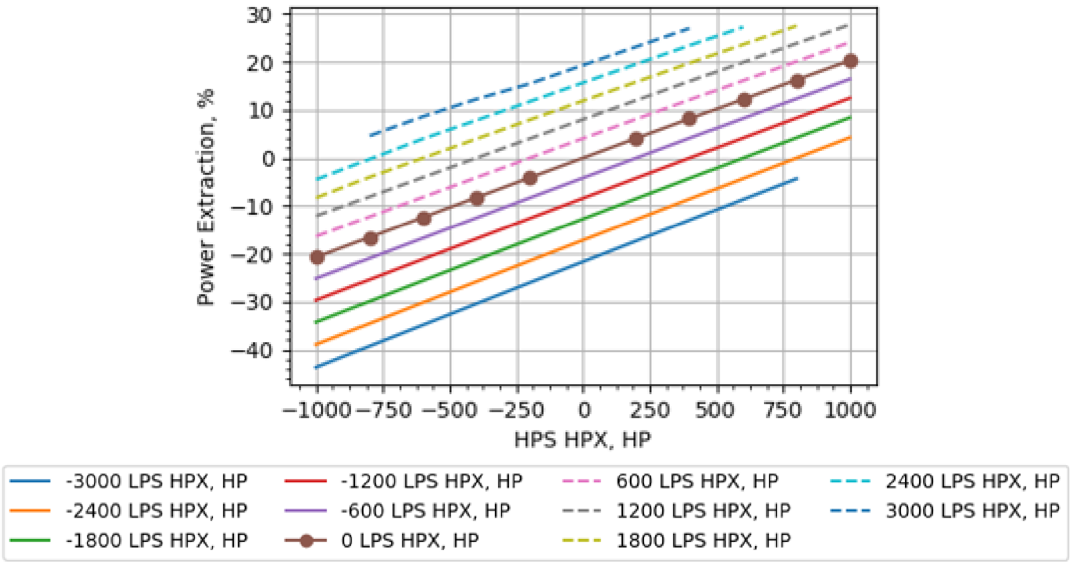

Figure 9.—Engine power extraction by percent, with power extraction and insertion for the low- and high-pressure spools at cruise with constant thrust.

# 4.0 Turbofan Operating Envelopes With Power Augmentation

Holding a maximum power level, as dictated by maximum turbine inlet temperature, two engine operating conditions can be examined, maximum possible power extraction and maximum thrust with power insertion or thrust assist. To determine the operational space, the engine was run at maximum turbine inlet temperature (3330 °R) and HPX was applied from –4000 to 4000 HP for the HPS and from –5000 to 5000 HP for the LPS at SLS conditions. Engine limits for maximum fan speed, maximum HPC speed, minimum fan stall margin, and minimum LPC stall margin were set to 104, 104, 5, and 15 percent, respectively. Traces of thrust, turbine inlet temperature, fuel flow, and total power augmentation are shown in Figure 10, where blue is low and red is high. In each trace the operational envelope is marked by the constant turbine inlet temperature. This target temperature is adjusted only when an engine operational limit is reached. When a speed limit is reached, temperature begins to fall off as fuel is removed from the engine. When a stall limit is reached temperature begins to increase to maintain component speed.

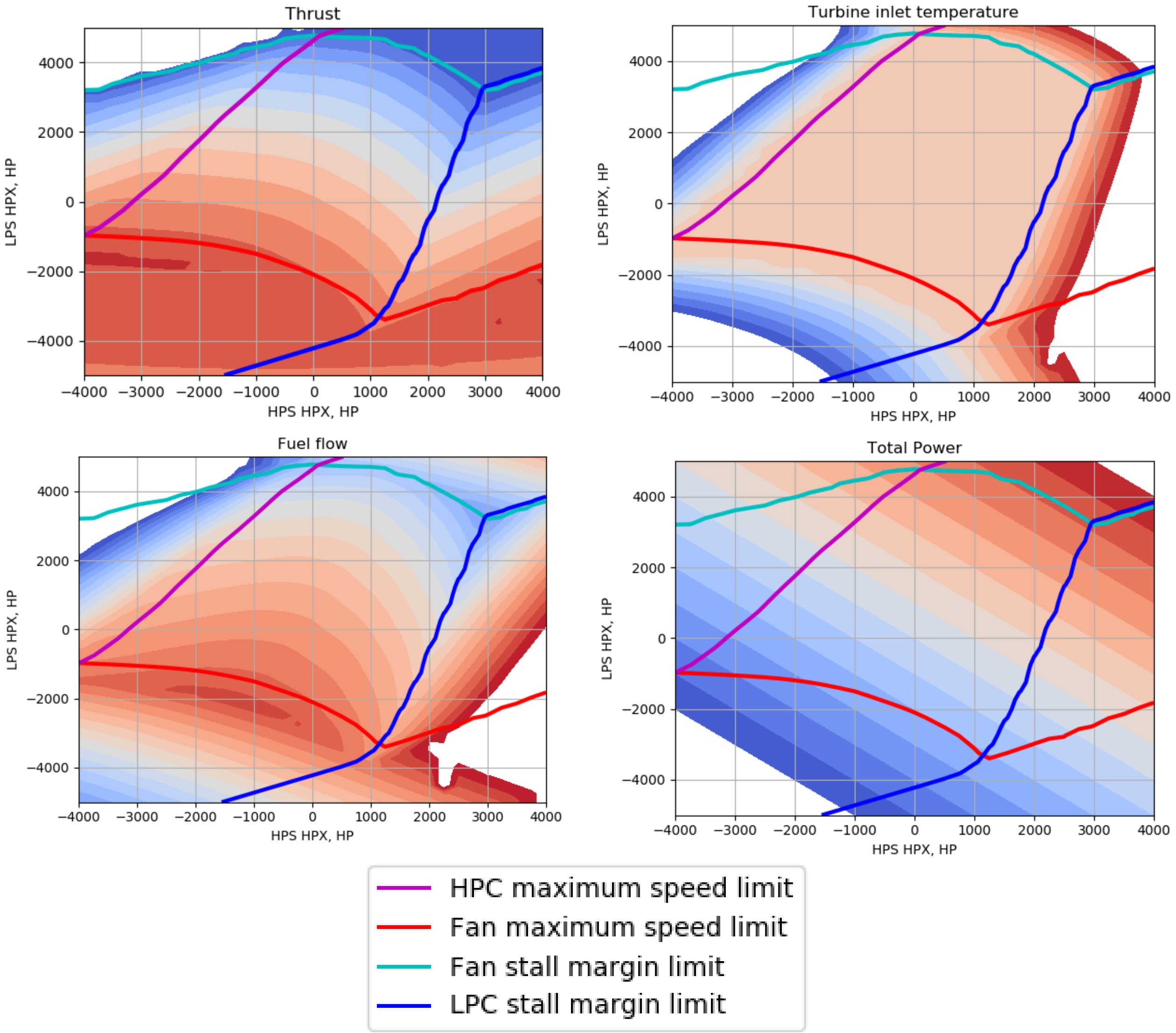

Figure 10.—Engine operational envelope (SLS) with power extraction and insertion for the low- and high-pressure spools at maximum turbine inlet temperature.

Considering thrust assist, a maximum thrust of 21120 lbf from a baseline thrust of 18920 lbf, 12 percent increase in thrust is reached. This is achieved at roughly 1000 HP LPS insertion and 4000 HP HPS insertion (5000 HP total), where the fan and HPC maximum speeds are reached. Comparing thrust, fuel flow, and power augmentation shows that these maximum thrust numbers come with a high-power insertion cost and fuel flow consumption is also increased. Depending on the application, a maximum thrust of 20759 lbf (10 percent increase in thrust) can be reached utilizing LPS insertion of 2000 HP.

Considering maximum power extraction, a maximum extraction is achieved where the fan and LPC stall margin limits are reached, roughly 2750 and 3250 HP power extraction from the HPS and LPS, respectively (6000 HP total extraction). This equates to 61 percent power extraction, as compared with LPT power output at that operating point, or 40 percent power extraction, as compared with LPT power output at the design point. At this operational point it can be seen that fuel flow has decreased to 6272 from 8040 lbm/hr (20 percent drop) and thrust has reduced to 10700 from 18920 lbf (57 percent drop). These traces demonstrate that balancing power extraction between the two spools is necessary for maximum power extraction. In this case if power extraction was taken only from the LPS, roughly 4500 HP could be achieved and if it was solely taken from the HPS roughly 2000 HPS would be extracted, which would be 25 and 66 percent less than the achievable power extraction with the power split between the shafts.

This study was also run at cruise conditions, 0.8 MN and 35000 ft. Results look similar to the ones performed at SLS with the exception of magnitudes and the high extraction limiting factor. In the cruise condition the fan stall margin is not reached. Instead, a minimum fan speed was observed that allows the cycle to maintain adequate nozzle pressure ratio (65 percent maximum fan speed). Traces can be found in Appendix A, where it is shown that power insertion raises the overall thrust of the engine from a nominal value of 3437 to 3844 lbf (at –500 HPX HPS, 0 HPX LPS), or an increase of 12 percent thrust. Maximum power extraction is achieved at the intersection of the minimum fan speed limit and the LPC surge margin limit achieving 2250 HP. (850 HPX HPS and 1400 HPX LPS) This results in 70 percent power extraction compared with LPT power generation at the operating point, or 46 percent power extraction when compared with LPT power generation at the nominal operating point. With this power extraction, thrust is reduced to 1658 lbf, or a reduction of 52 percent from the nominal operating thrust.

To gain more insight into efficiency, a thrust specific power consumption (TSPC) was calculated for the SLS case, as shown in Figure 11. Here the energy content of the fuel (multiplied by the efficiency) and the power augmentation were combined then divided by total thrust. In this way a metric similar to thrust SFC was calculated. This metric has meaning only when considering thrust assist and is not meaningful when power is being removed from the engine for external propulsors, as the extra thrust generated is not being accounted for. Looking at the TSPC, it may be observed that the lowest (most efficient) values can be found when LPS is the dominant power insertion mechanism, with the lowest TSPC close to where the LPC stall margin and fan max speed limit are reached (this point actually has some HPS extraction). Though this metric shows how efficient the overall system is, it does not differentiate between fuel energy and energy from an external source. To understand how effective power insertion is at thrust, a thrust specific power augmentation is developed. This consists of the power augmentation divided by the difference in thrust when compared with the engine with no power augmentation (note: power insertion is negative, and the thrust difference is positive when thrust is gained). In this way a power per thrust gained can be calculated. Looking at Figure 11, the green line shows a thrust neutral configuration, where no additional thrust is generated. Values above the green line show a thrust loss and values below demonstrate a thrust gain. Considering only areas with thrust gain, it can be seen that the lowest power per additional thrust is achieved with large LPS insertion. It should be noted that the white areas are singularities where additional thrust approaches zero or where power insertion causes a loss in thrust. This power augmentation analysis is useful in a case where a power insertion device (for example a battery) would need to be sized.

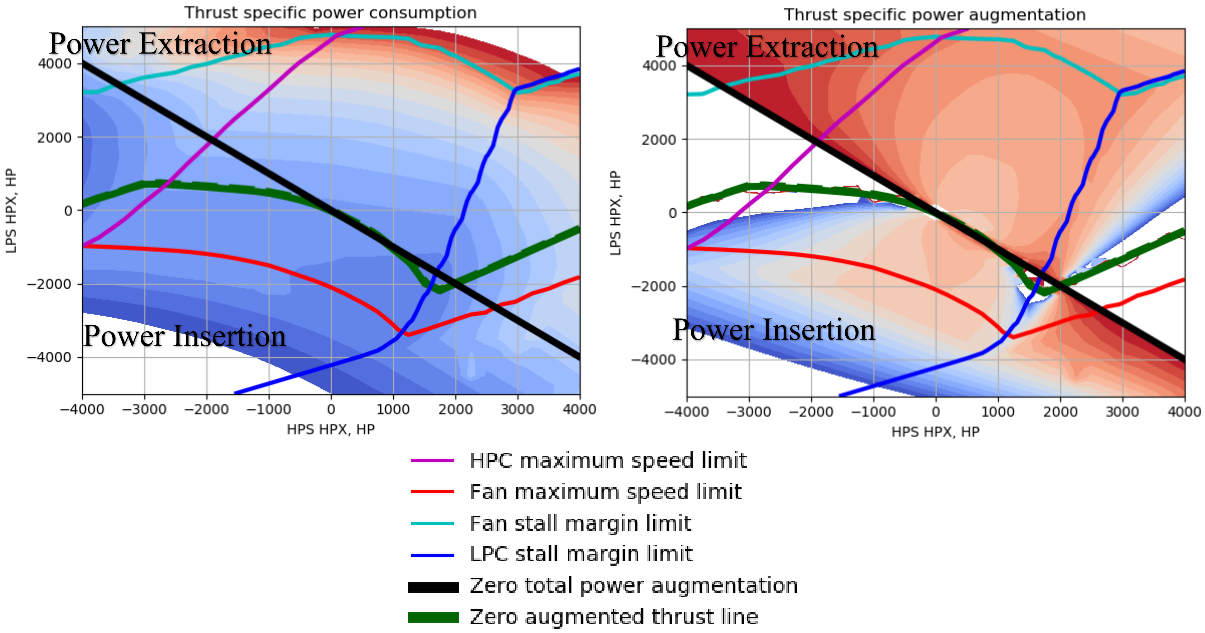

Figure 11.—Engine TSPC (left) and Engine thrust specific power augmentation (right) with power extraction and insertion (SLS) for the low- and high-pressure spools at maximum turbine inlet temperature.

Considering power extraction, thrust specific power augmentation in Figure 11 shows power extracted per thrust. In this case power is a positive number and thrust is negative, therefore low values (large negative numbers) show areas of large power extraction with relatively low thrust loss. Looking at the trace, it can be observed that the best power ratio changes a bit with total power extraction. For the maximum power extraction of 6000 HP, the trend suggests utilizing a power extraction ratio of roughly 34 percent (2000 HP HPS, 4000 HP LPS) results in the largest power extraction for the least amount of thrust loss.

Analysis has shown that off-design power extraction lowers maximum thrust output of the engine. As such, if power extraction is the goal, the engine must operate at a de-rated thrust point to meet demand. When operating below designed maximum thrust, power augmentation capability is determined by three potential limiting conditions, high turbine inlet temperature, low LPC stall margin, or high HPC shaft speed. To gain an understanding of this type of operational space, the engine described above is reduced to 85 percent SLS maximum thrust. Power augmentation is then applied to the engine until a limit is hit. For this study the turbine inlet temperature limit is set to 3330 °R, the LPC surge margin limit is set to 15 percent, and the HPC speed limit is set to 104 percent. Results from this analysis are shown in Figure 12. Here trends in thrust, total power augmentation, fuel flow, and total power extraction are shown along with limit thresholds to show an operational space. It should be noted that the temperature limit and stall margin limit meet with a slight amount of LPS power extraction, therefore if HPS power extraction is applied exclusively the engine will be stall margin limited. With these boundaries noted, it can be seen that thrust holds steady within the boundary and falls off when crossing the HPS speed or the HPT inlet temperature boundaries. Conversely, thrust increases when crossing the LPC stall margin boundary as more fuel is added to the engine. Looking at the contour for total power extraction, it can be seen that drawing power only from the LPS will generate more power than drawing only from the HPS, however drawing power with a power extraction ratio (HPS to total) of roughly 50 percent will generate the highest power extraction while maintaining thrust. Resulting in 2500 HP or 20 percent power extraction.

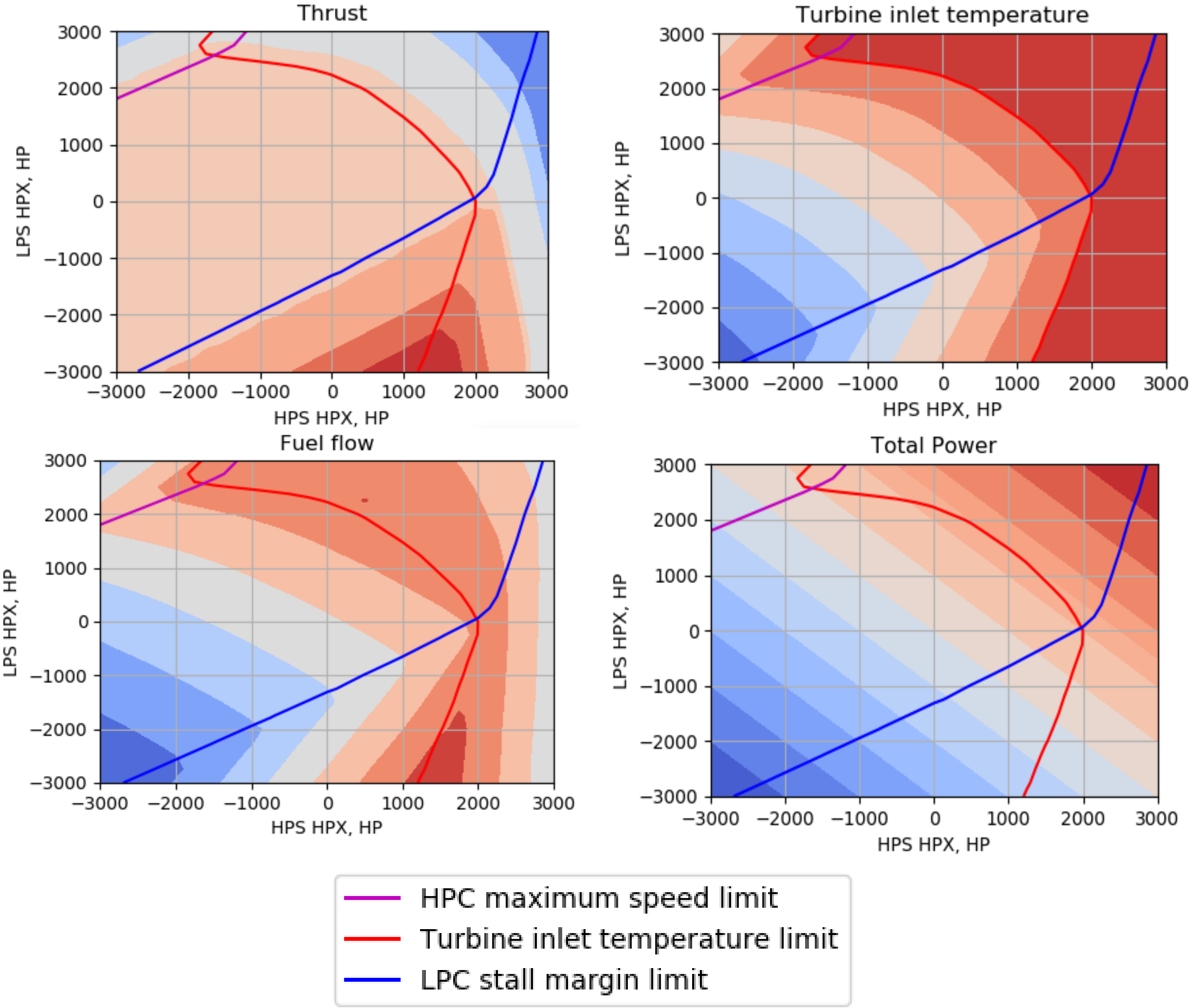

Figure 12.—Engine operational envelope with power extraction and insertion for the low- and high-pressure spools with 85 percent max thrust at SLS.

In addition to the metrics developed, a power specific fuel consumption (PSFC) was also calculated. As mentioned above specific fuel consumption is difficult to interpret when power and thrust are changing. In this study, thrust is held constant within the non-limited region therefore a PSFC can be used to determine the fuel cost of generating power. To calculate the PSFC, fuel flow without power augmentation was subtracted from fuel flow with power augmentation and then divided by the total power augmentation, calculating a fuel flow per power metric, as shown in Figure 13. For power extraction a lower PSFC represents more efficient power generation. Conversely, for power injection, a higher PSFC represents an engine that is utilizing more of the power to reduce fuel flow or more efficient power utilization. It should be noted some points with very high or very low values were neglected from the trace in regions of poor performance or at singularities. Despite this, the figure shows that power extraction PSFC is reduced as HPS extraction is increased and power insertion PSFC is increased as HPS insertion is increased. Additionally, the lowest PSFC values for total power extraction utilize a portion of LPS power insertion. Given this, if power generation goals are not met by an HPS dominated power extraction there may be some efficiency benefit to further reducing engine thrust output to gain more margin.

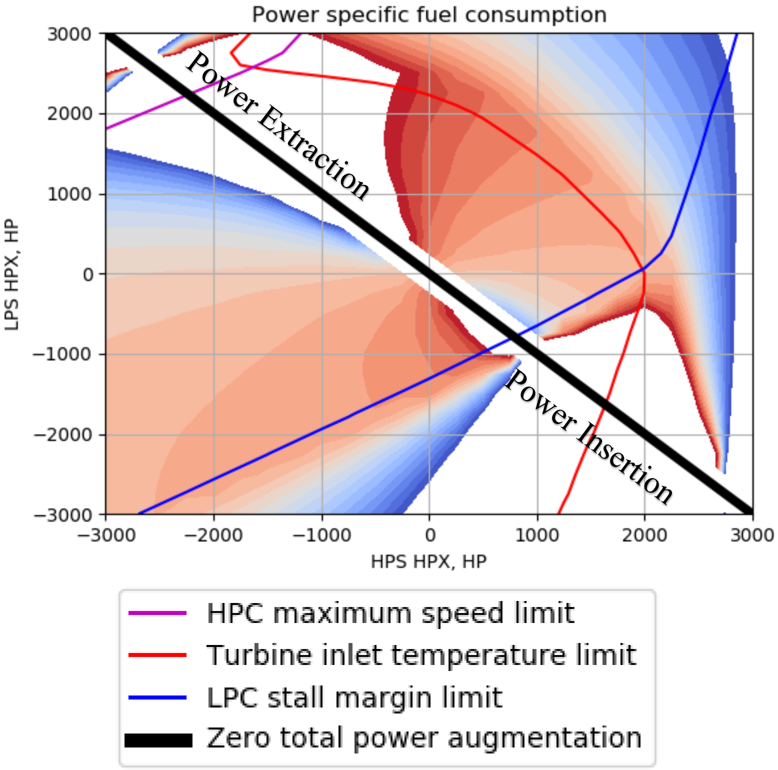

Figure 13.—Engine power SFC with power extraction and insertion for the low- and high-pressure spools with 85 percent max thrust at SLS.

## 5.0 Variable Geometry Study

In gas turbine engines, it is typical to utilize variable geometries to correct off design behavior. A simple study of the effects of a variety of variable geometries was completed to understand their potential use for expanding the power augmentation envelope. Methods for simulating the effects of each considered variable geometry is discussed in turn. The VAFN and VACN were simulated by increasing nozzle throat area. The VBV was simulated by increasing bypass air from station 25 to the bypass stream. Each of the variable angle components (HPC VSV, LPC IGV, and VPF) was simulated by scaling the compressor performance maps to achieve a lower pressure ratio and corrected mass flow, as described within Reference 2. For simplicity, each variable geometry is evaluated independently and in the context of the two mission types, thrust assist (constant turbine inlet temperature, Figure 14) or power extraction (constant thrust, Figure 15).

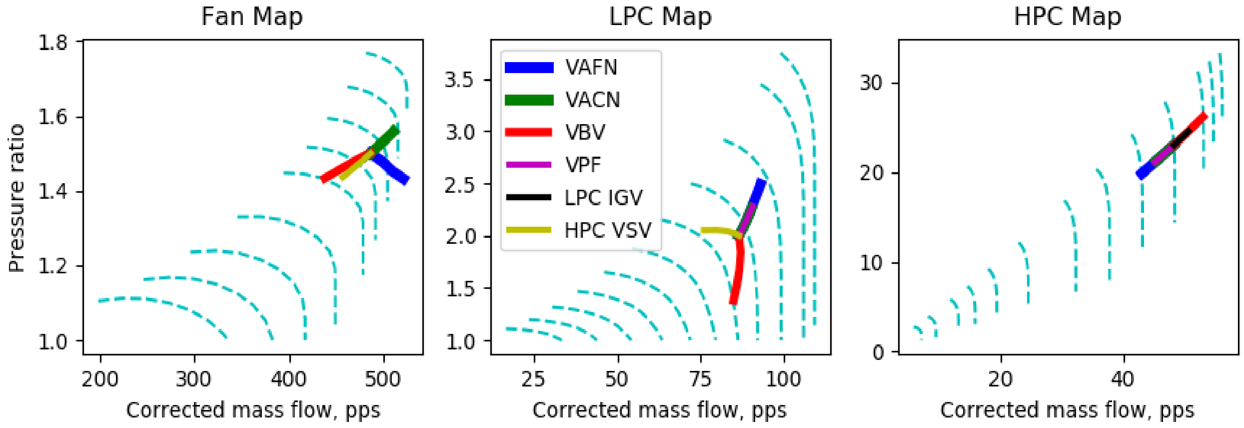

Figure 14.—Compressor maps adjusting variable geometries at SLS, with constant turbine inlet temperature.

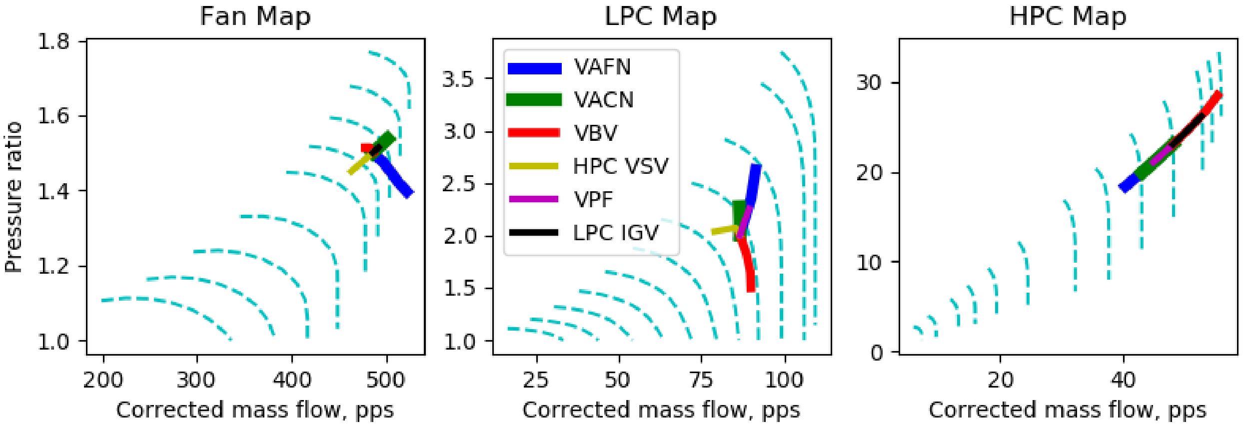

Figure 15.—Compressor maps adjusting variable geometries at SLS, with 100 percent maximum thrust.

1. **VAFN**: The VAFN offers a promising handle for system adjustment. As the VAFN is opened fan pressure ratio is reduced and mass flow is increased, demonstrating an ability to shift fan performance. This decrease in pressure ratio reduces the load on the overall engine, increasing the LPC speed and decreasing the HPC speed. For LPS power extraction this unloading is desirable, as adding load to the LPS will result in the opposite effect.
2. **VACN**: Opening the VACN has a similar effect as the VAFN. The main difference is that it causes an increase in fan pressure ratio as more power is diverted from back pressuring the engine to the fan. Care must be taken when performing this operation however because adequate nozzle pressure ratio must be maintained throughout the performance envelope. Closing the VACN will have the effect of pushing up nozzle pressure ratio, which will cause an overall loss in energy.
3. **VBV**: Diverting air from station 25 to station 15 causes a sharp increase in LPC stall margin and drives the HPC speed higher. These effects could be used to counter act HPS power extraction or LPS power insertion. This would only be suggested during transient operation however, because work has been done on this air and bypassing it results in engine efficiency loss.
4. **HPC VSV**: Closing the HPC VSVs has the effect of lowering the mass flow and pressure ratio of the HPC, which speeds up the HPS. This reduction in pressure ratio drops the OPR of the engine. Opening the VSVs decreases the HPS speed, increasing HPC pressure ratio and could potentially be used to offset HPS power insertion effects.
5. **VPF**: Adjusting the angle of the fan blades has a similar effect as opening and closing the VAFN and will act to load and unload the LPS. This direct control on power used by the fan allows a designer to adjust thrust as necessary to achieve a desired LPS power augmentation, while maintaining operability requirements.
6. **LPC IGV**: Closing the LPC IGVs reduces the mass flow and pressure ratio of the LPC. This causes the HPC to increase in speed and lowers OPR, which reduces cycle efficiency. Opening the LPC IGVs increases the mass flow and pressure ratio which could be used counteract the effects of LPS power insertion.

These variable geometries have been looked at for this study, however many of them are not common to commercial gas turbines. In practice an engine may contain a VBV, HPC VSVs, or LPC IGVs. The VAFN, VACN, and VPF are advanced technologies, where more research would be required to implement. Although a basic outline of the usefulness of each of these geometries has been laid out, more research is required to identify the advantages of using them. In many cases adopting adequate HPS to LPS power split would suffice for operability eliminating the need for additional variable geometries. Additionally, in some cases variable geometry requirements may be relaxed or the eliminated by using power augmentation. As an example, LPS power extraction could be used in cases of high LPC loading to increase stall margin, reducing the requirements for a VBV (Ref. 11).

## 6.0 Summary and Conclusions

This paper details the effects of power augmentation (extraction and/or insertion) on a turbofan engine. The importance of understanding power augmentation has grown as more electric aircraft and electrified aircraft propulsion concepts have become more popular. Three main applications of power augmentation are reviewed in detail, maximum power extraction, maximum power extraction at constant thrust, and power insertion for thrust assist applications. Additionally, strategies for maximizing power augmentation utilizing spool choice (high pressure spool to lower pressure spool) are reviewed and operational envelopes are developed to visualize the operating space. In this examination it was determined the limiting factors to power augmentation are fan maximum speed, high pressure compressor maximum speed, fan minimum speed, low pressure compressor stall margin, and fan stall margin. Results shows show that maximum achievable power extraction is 61 percent with a 57 percent loss of thrust. Assuming an 85 percent thrust requirement, a maximum power extraction of 20 percent is achievable. Utilizing power insertion, a thrust assist of 12 percent over the baseline is achieved. In each case it is shown that spool choice effects engine response, as the effects of high-pressure spool augmentation can be negated by applying power augmentation on the low-pressure spool. Because of this, maximum power augmentation generally requires the use of both spools in concert. Spool choice is also shown to have an effect on the efficiency of power extraction or thrust generation that is dependent on mission.

# Appendix—Operating Envelopes for Cruise Operation

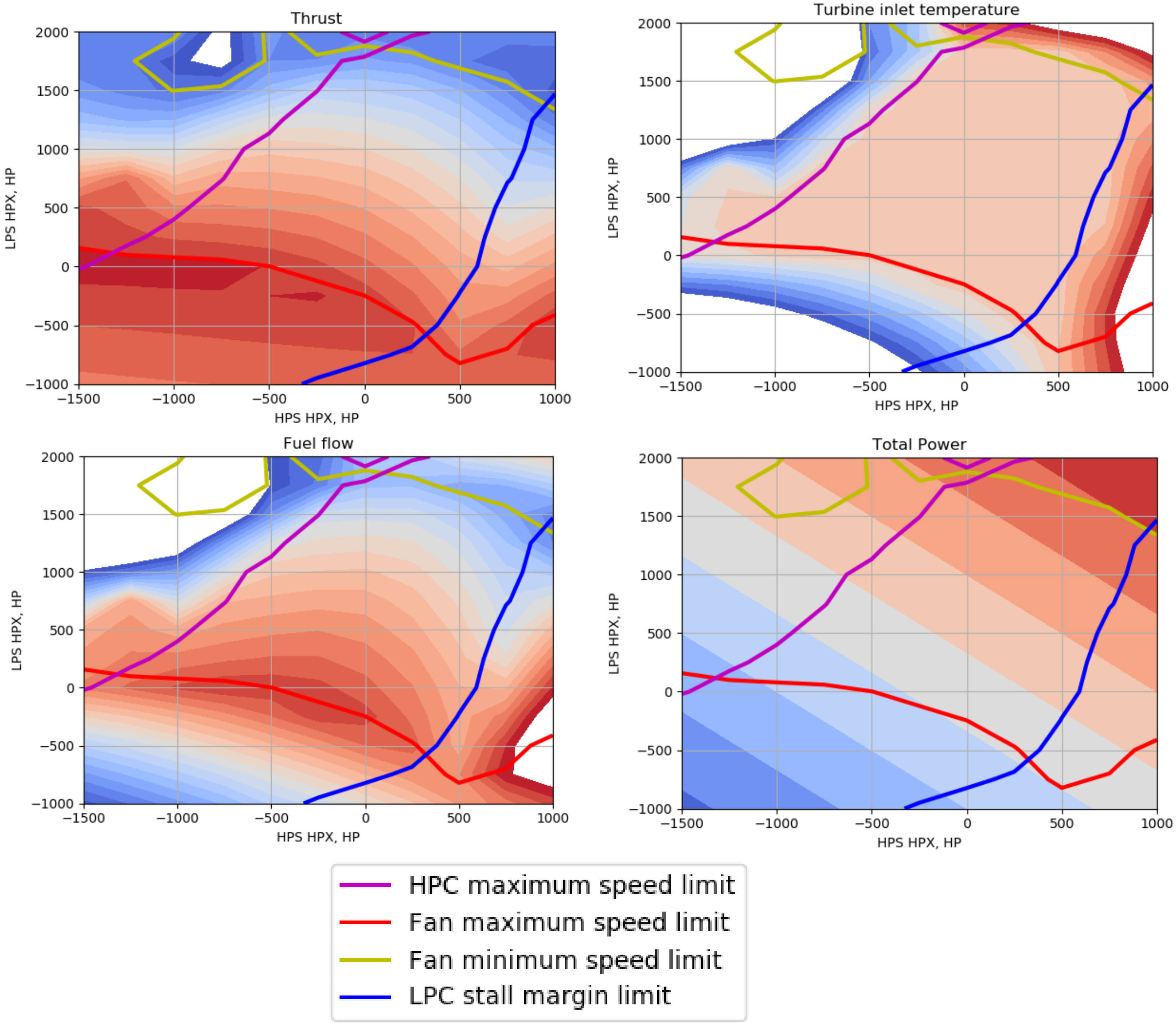

Figure 16.—Engine operational envelope (Cruise) with power extraction and insertion for the low- and high-pressure spools at maximum turbine inlet temperature, where blue is low and red is high.

# References

1. I. Moir, A. Seabridge, and M. Jukes, “Electrical Systems,” in Civil Avionics Systems 2nd Edition, ISBN: 978-1-118-34180-3, ed: John Wiley & Sons, 2013, pp. 235–290.
2. Kurzke, J., Halliwell, I., “Propulsion and Power: An Exploration of Gas Trubine Performance Modeling,” Springer International Publishing AG, part of Springer Nature, 2018.
3. Jansen, J.H., Bowman, C., Jankovsky, A., Dyson, R., Felder, J., “Overview of NASA Electrified Aircraft Propulsion Research for Large Subsonic Transports,” AIAA Propulsion and Energy Forum, Atlanta, GA. 2017.
4. Madonna, V., Giangrande, P., Galea, M., “Electrical Power Generation in Aircraft: Review, Challenges and Opportunities,” IEEE Transactions on Transportation Electrification, vol. 4, issue 3, pg. 646–659, Sept. 2018.
5. Walters, E., Iden, S., McCarthy, K., Amrhein, M., O’Connell, T., Raczkowski, B., Wells, J., Lamm, P., Wolff, M., Yerkes, K., Borger, W., Wampler, B., “INVENT Modeling, Simulation, Analysis and Optimization,” AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, AIAA 2010-287, Orlando, FL, Jan. 4–7, 2010.
6. Welstead, J.R., Felder, J.L., “Conceptual Design of a Single-Aisle Turboelectric Commercial Transport with Fuselage Boundary Layer Ingestion,” AIAA SciTech Forum, San Diego, CA. 2016.
7. Antcliff, K., Capristan, F., “Conceptual Design of the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) Concept,” 18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, AIAA 2017-4001, Denver, CO, June 5–9, 2017.
8. Lents, C., Hardin, L., “Fuel Burn and Energy Consumption Reductions of a Single-Aisle Class Parallel Hybrid Propulsion System,” AIAA Propulsion and Energy forum, AIAA 2019-4396, Indianapolis, IN, Aug. 19–22, 2019.
9. Scholz, D., Seresinhe, R., Staack, I., Lawson, C., “Fuel Consumption Due to Shaft Power Off-Takes from the Engine,” International Workshop on Aircraft System Technologies, Hamburg, Germany, April 23–24, 2013.
10. Faidi, A., “Effect of Accessory Power Take-Off Variation on a Turbofan Engine Performance,” Thesis, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH, Sept. 2012.
11. Culley, D., Kratz, J., and Thomas, G., “Turbine Electrified Energy Management (TEEM) For Enabling More Efficient Engine Designs,” AIAA Propulsion & Energy Forum, Cincinnati, OH. 2018.
12. Kratz, J., Culley, D., and Thomas, G., “A Control Strategy for Turbine Electrified Energy Management,” AIAA Propulsion & Energy Forum, Indianapolis, IN, 2019.
13. Kratz, J., Culley, D., and Thomas, G., “Evaluation of Electrical System Requirements for Implementing Turbine Electrified Energy Management,” AIAA Propulsion & Energy Forum, Indianapolis, IN, 2019.
14. Jones, S., “An Introduction to Thermodynamic Performance Analysis of Aircraft Gas Turbine Engine Cycles Using the Numerical Propulsion System Simulation Code,” NASA/TM—2007-214690, March 2007.
15. Daly, M., Gunston, B., *Jane’s Aero Engines*, 35 ed., Jane’s Information Group, Alexandria, Virginia, April 2015.
16. Federal Aviation Administration: *rgl.faa.gov*, cited as of 1/16/2020.
17. European Union Aviation Safety Agency: *EASA*, cited as of 1/16/2020.