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Ideal Power Output - An Alternative Aircraft Engine Performance Comparator

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1.0 ABSTRACT

The gas turbine is applied in four basic configurations; the turbojet, the turbofan, the turboprop and the turboshaft. Comparisons of the performance of these various configurations is difficult since they convert the energy to different forms , i.e. thrust or shaft power. Cycle variables which do not necessarily constitute advancements in the state-of-the-art such as bypass ratio and fan pressure ratio can have a profound effect on thrust and shaft power. Differences in flight speed and altitude capability further confound the comparisons. What is required is a comparison methodology that removes all of these variables and yet puts all the various types of engines on an equitable basis. This paper will provide such a comparison tool. All turbomachinery, regardless of configuration, can be compared with this method.

2.0 NOMENCLATURE

BPR = engine bypass ratio
Cp = specific heat at constant pressure, BTU/(lbm-R)
Delta = differential or loss in cycle
Eta = efficiency
h = enthalpy, BTU/lbm
HP = high pressure
HPC = high pressure compressor
IPFC = ideal power fuel consumption, hp/lbm/hr
ISPO = ideal specific power output, hp/lbm/s
LPC = low pressure compressor
m = mass flow rate, lbm/s
OPR = overall compressor pressure ratio
P = pressure, psi
P/P = pressure ratio
hp = shaft horsepower, hp
T = temperature
W = specific work, BTU/lbm
γ = ratio of specific heats

Subscripts

amb = ambient condition
ex = engine nozzle exhaust
rel = relative condition for isentropic process
T21 = total condition at fan inlet
T25 = total condition at high pressure compressor inlet
T3 = total conditon at compressor exit
T4 = total condition at combustor exit
T45 = total condition at low pressure turbine inlet
T5 = total condition at low pressure turbine exit

3.0 INTRODUCTION

A detailed description of the methodology will be discussed in this paper. The method relies on calculating the residual power after the energy required to drive the core engine is extracted. Careful attention must be paid to account for the power expended on various non-core related power absorption elements such as the bypass stream in a turbofan engine. Ideal power output is then normalized to provide a size-independent way to compare power output and fuel consumption characteristics for the various engine types. The effects of cycle parameters such as turbine inlet temperature and overall pressure ratio on these performance indices will be used to highlight the utility of the method. Historical trends for various existing engines will be provided to show progress that has been made in the area of gas turbine engine development. Finally, the ideal power concept will be used to make projections for what cycles are needed in future engine development.

4.0 IDEAL POWER FOR THE PERFECT TURBOJET

In order to understand the ideal power concept, it is useful to consider the simplest cycle, the "perfect turbojet engine." A perfect engine is one which has no internal losses. All efficiencies are 100%. There are no leakages, pressure drops nor air offtakes for cooling, customer services, etc.. On a Temperature versus Entropy (T-S) diagram (see Figure 1), compression and turbine expansion are accomplished isentropically along with a perfect heat addition process, i.e., all fuel energy is converted to heat with no pressure losses. Note that for the perfect turbojet case, compressor pressure ratio and turbine inlet temperature are the primary cycle design variables. The residual pressure remaining after the turbine has extracted the necessary compressor work is expanded through a nozzle to provide thrust. Unfortunately, thrust is not as clear a performance indicator as horsepower, particularly when comparing various engine types such as turbofans and turbojets.

To calculate ideal power output, it is necessary to replace

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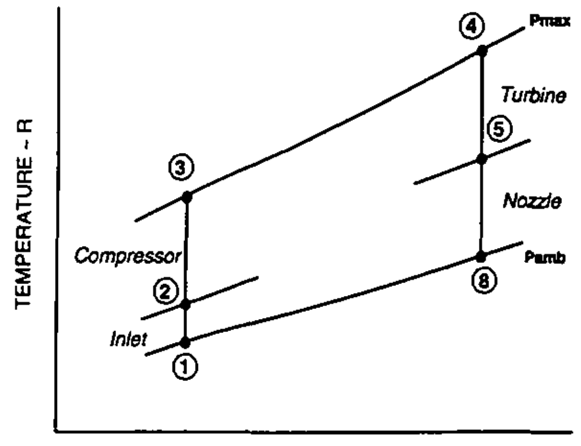

Figure 1 - T-S Diagram for the Perfect Turbojet

the nozzle with an isentropic power turbine which expands to ambient pressure. In other words, the nozzle momentum thrust is converted into shaft horsepower. This ideal power output is a function of engine size, however, and must be normalized to be size independent. The term "Ideal Specific Power Output" (ISPO) is defined as ,

$$ISPO = \frac{\text{Ideal Power}}{\text{Engine Airflow}} \text{ (hp/lbm/sec)} \quad (1)$$

and "Ideal Power Fuel Consumption" (IPFC)

$$\text{IPFC} = \frac{\text{Ideal Power}}{\text{Fuel Flow}} \text{ (hp/lbm/hr)} \quad (2)$$

Ideal Specific Power Output (ISPO) is a good indicator of power density, and as such can be used to compare various perfect turbojet cycles. Increasing ISPO indicates an improvement in capability. Figure 2 shows overall pressure ratio (OPR) versus specific power ISPO for lines of constant turbine inlet temperature (T_{T4}). The flight condition illustrated is at sea level static, although any condition could be used for comparison purposes. Note that for a given T_{T4}, there is an OPR that provides the maximum specific power. Alternatively, as T_{T4} increases, the peak specific power occurs at a higher OPR. To

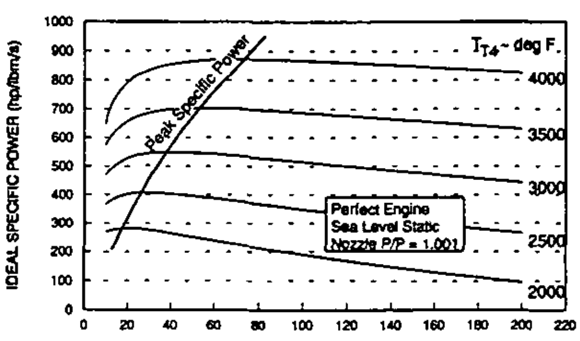

Figure 2 - Ideal Specific Power Output

understand this phenomenon, it is useful to consider the cycle parameters from their extreme conditions. The compressor exit temperature (T_{T3}) is the result of an isentropic compression process, and therefore, the higher the pressure ratio, the higher the T_{T3}. In the limit, the T_{T3} will equal the combustor exit temperature such that no heat is added to the cycle. Under this condition, the pressure ratio is maximum for a given T_{T4}, but no net work is output since no heat was added. Viewing the sea level static performance from the other extreme, if the compressor pressure ratio is 1.0, i.e., T_{T3} equals ambient temperature, the net power output is zero regardless of T_{T4}. Hence, there exists a overall pressure ratio between the two extremes which maximizes horsepower output. For a calorically perfect gas (Cp and Gamma are constant), it can be shown that (Ref. 1 - Durham, 1951) the peak power output for a given T_{T4} occurs when

$$OPR\,(@\ Peak\ ISPO) = \left(T_{T4} / T_{amb}\right)^{\frac{\gamma}{2(\gamma-1)}} \quad (3)$$

When accounting for real gas effects, the peak ISPO occurs at a higher overall pressure ratio. But this formula is useful for a first pass prediction at the OPR where peak ISPO occurs. If an estimate for the average Gamma (γ) from ambient to the turbine inlet temperature is assumed, a rather accurate first guess of this OPR can be found.

Ideal Power Fuel Consumption (IPFC) is a good indicator of fuel efficiency. An increase in IPFC indicates an increase in horsepower output for a given fuel flow rate. Figure 3 illustrates the effect of OPR versus IPFC for lines of constant T_{T4} for the perfect turbojet at sea level static. The line associated with the previously mentioned peak ISPO is plotted for interest. Note that the peak ISPO does not occur at the same OPR as the maximum IPFC. In fact, for a given operating condition, there is a pressure ratio

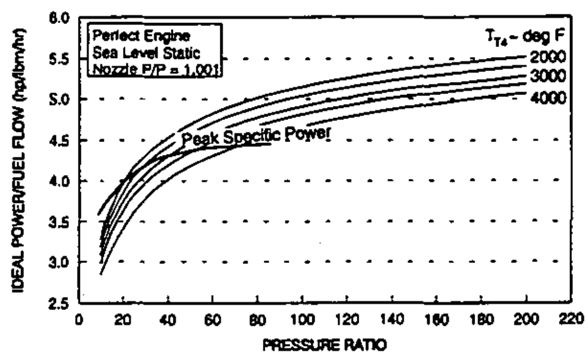

Figure 3 - Ideal Power Output per Unit Fuel

such that the net specific power output is a maximum but the power specific fuel consumption is *not* a maximum. The maximum IPFC always occurs at a higher OPR than the OPR associated with the peak ISPO. This is true for the real engine case, as well.

When real component losses are included in the cycle, the peak ISPO and peak IPFC shift to a lower OPR. Figure 4 illustrates the effect of real engine cycle characteristics on both ideal power performance parameters. Note that while the peak ISPO and IPFC shifted to a lower pressure ratio, the peak IPFC always occurs at a higher OPR than the peak ISPO. Hence, when selecting a cycle for a future aircraft, the "optimum" OPR and T_{T4} will be a compromise between the value associated with maximum ISPO and maximum IPFC. Aircraft requirements such as low fuel consumption for a transport or high point performance for a fighter will drive the solution in one direction or the other.

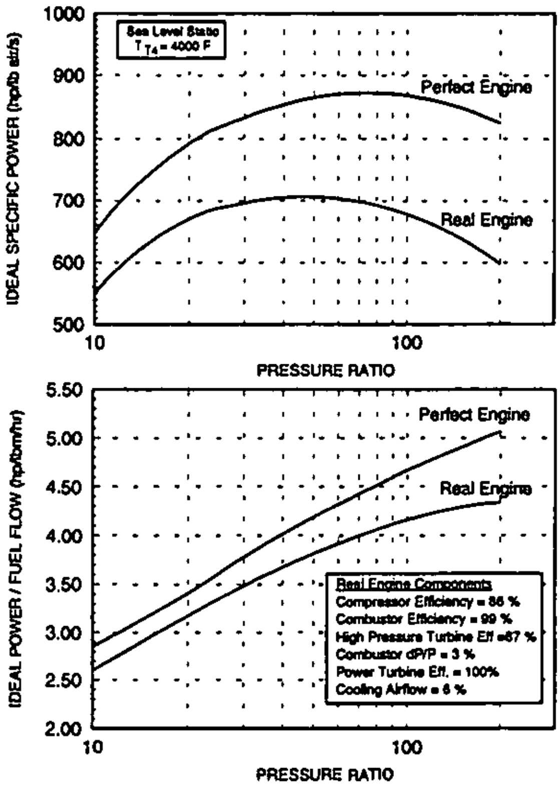

Figure 4 - Real Engine Effects on Ideal Power Performance Indicators

5.0 IDEAL POWER OUTPUT FOR ALTERNATIVE CONFIGURATIONS

Any gas turbine engine cycle can be analyzed using the ideal power output performance indicators. Consider an unmixed dual spool turbofan. There are two basic streams, the fan stream and the main (core) stream. In order to calculate ideal power output, the cycle must be converted into a turboshaft configuration, with accurate accounting of all expended power (see Figure 5). The main stream is the flow path that produces the power output of the engine. The fan tip stream pressurizes the bypass flow and this flow, in turn, is expelled through a nozzle to produce momentum thrust. The energy to pressurize the bypass stream can be dismissed in this analysis process. The portion of the fan that passes and pressurizes the main stream flow participates directly in the energy exchange in the main combustor and therefore must be accounted for in this analysis. This increment of work associated with the "supercharging" of the core stream must be supplied by a

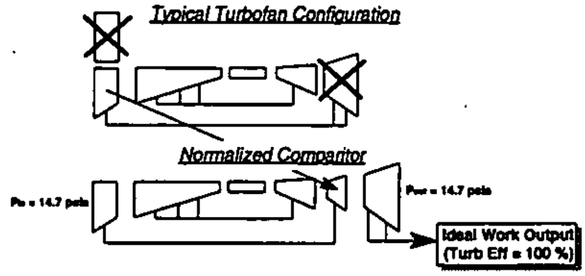

Figure 5 - Turbofan Cycle Ideal Power Output Comparitor Concept

portion of the low pressure turbine. The other increment of work supplied by the low pressure turbine, that associated with the fan bypass stream, must be added back to the system. In Figure 5, the comparitor cycle is converted to a dual spool turboshaft with a free power turbine.

To effect the comparison, the thermodynamic performance levels of the various engine components are required. Input parameters required for the cycle model include: the core flow, fan root pressure ratio and efficiency, high pressure compressor pressure ratio and efficiency, combustor efficiency and pressure drop, high pressure turbine cooling flow and efficiency, low pressure turbine cooling flow and efficiency, and any other appropriate flow path losses. For greatest accuracy when converting the low pressure turbine to drive just the core fan stream, the new low pressure turbine work requirement should be computed based on the polytropic efficiency of the original turbine. Polytropic efficiency assumes equal efficiency for each incremental change in enthalpy, so it properly accounts for the turbine reheat effect. The impact of assuming a constant adiabatic efficiency between the two low pressure turbines is fairly small, however, so this is the method used by the authors. A complete isentropic expansion through the power turbine to ambient pressure is used to determine ideal power output. The use of an isentropic power turbine is justified because it represents the maximum power output possible for the engine being compared and it puts all engines on an equitable footing.

An example is used to illustrate the calculation of ideal power output for a given turbofan cycle. Consider a high bypass ratio turbofan with the cycle characteristics shown in Table 1. The conversion process is shown below. Note that the calculations of temperatures and pressures for various engine stations are not shown since cycle calculation of these parameters are well known.

	Turbofan	Normalized Comparitor
Airflow (lb/s)	700	100
BPR	6	—
OPR	40	40
P/P Fan	1.6	—
Eta Fan (%)	88	88
P/P LPC	4	4
Eta LPC (%)	87	87
P/P HPC	10	10
Eta HPC (%)	86	86
Delta P/P Comb.(%)	95	95
T_{T4} (R)	3131	3131
T_{T41} (R)	3060	3060
ETA HPT (%)	90	90
ETA LPT (%)	91	91
HP Stator Cooling (%)	5	5
HP Rotor Cooling (%)	5	5
ISPO (hp/lbm/s)	—	306.1
IPFC (hp/lb fuel/hr)	—	3.63

Table 1 - Conversion of Turbofan Cycle to Comparitor

Step 1: Calculation of the work associated with the core stream portion of the fan.

Given;

$T_{T21} = 518.7\,^0R$, $T_{T25} = 810\,^0R$, (from cycle analysis)

$h_{T21} = 124.0$ BTU/lbm, $h_{T25} = 194.14$ BTU/lbm (from gas tables)

$m_{core} = 100$ lbm/s

Find fan core work ($W_{fan\,core}$);

$W_{fan\,core} = m_{core}(h_{T25} - h_{T21})$

$= 100$ lbm/s $(194.14 - 124.0)$ BTU/lbm

$W_{fan\,core} = 7014$ BTU/lbm

Step 2: Calculate low pressure turbine (LPT) required to drive the core stream fan and get exit conditions.

Given;

$T_{T45} = 2320\,^0R$, $m_{45} = 102.3$ lbm/s, fuel/air = 0.0235 (from cycle analysis)

$h_{45} = 612.90$ BTU/lbm, $p_{rel45} = 376.72$ psi (from gas tables)

$W_{LPT} = W_{fan\,core} = 7014$ BTU/lbm

Find T_{T5}, $P_{rel\,5}$;

$W_{LPT} = m_{45}(h_{T5} - h_{T45})$

$h_{T5} = (W_{LPT}/m_{45}) + h_{T45}$

$= (7014$ BTU/lbm/102.3 lbm/s$) + 612.90$ BTU/lbm

$h_{T5} = 544.37$ BTU/lbm

Thus from gas tables;

$T_{T5} = 2089\,^0R$, $P_{rel5} = 239.44$ psi

$P_{T5} = (P_{rel5}/P_{rel45})*P_{T45} = (239.44/376.72)*151.30$

$P_{T5} = 96.16$ psi

Step 3: Calculate ideal specific power output (ISPO) by isentropic expansion through the power turbine.

Given;

$P_{rel5} = 239.44$ psi, $P_{T5} = 96.16$ psi

$h_{T5} = 544.37$ BTU/lbm, $P_{amb} = 14.696$ psi

Find h_{amb}, ISPO;

$(P_{rel5}/P_{rel\,amb}) = (P_{T5}/P_{amb}) = 96.16/14.696 = 6.54$

$P_{rel\,ex} = 239.44/6.54 = 36.59$ psi

$h_{ex} = 328.04$ BTU/lbm (from gas tables)

So, Specific Power becomes

ISPO $= (h_{T5} - h_{ex})(1.415$ hp-s/BTU$)$

$= (544.37 - 328.04)$(BTU/lbm)(1.415 hp-s/BTU)

ISPO = 306.1 hp/lbm/s

6.0 TECHNOLOGY COMPARISON

A representative mix of ten production engines and two advanced study engines have been used in the comparison for this paper. The production engines include a broad mix of turbojets and turbofans for fighters, bombers, and transport aircraft. The turbofan engines include low, medium, and high bypass configurations. Table 2 summarizes the converted turboshafi cycle characteristics for the various production and advanced study engines. The production engines range in OPR from 10 to 37 and turbine rotor inlet temperatures (T_{T41}) to near 2800°F. The production engines show a continuous improvement in ISPO, with diminishing improvement in the most recent years. This does not necessarily mean that the turbine engine technology has reached a point of diminishing returns, but merely that the most recent engines have not aggressively pursued improvements in specific power output. The same could also be said for IPFC.

The advanced study engines include a medium bypass ratio mixed flow turbofan and a high bypass ratio separate flow turbofan. They are merely suggested configurations for discussion purposes, and do not represent any particular engine requirements. The advanced study engine

Production Engines	Year	OPR	TT41 - F	ISPO (SLS)	IPFC (SLS)
A	1957	12.2	1700	112.2	2.21
B	1963	9.2	2200	208.5	2.54
C	1968	20.9	2042	170.9	3.25
D	1968	21.2	2225	228.2	3.16
E	1972	24.9	2305	213.0	3.00
F	1984	26.8	2491	248.7	3.07
G	1987	30.9	2567	297.3	3.46
H	1991	30.4	2520	261.1	3.23
J	1991	30.9	2483	242.9	3.25
K	1994	36.9	2603	298.1	3.35
Advanced Engines					
I	2003	55	3466	516.9	3.80
II	2009	100	3609	605.2	4.27

Table 2 - Converted Turboshaft Engine Cycle Characteristics

performance levels are made possible by the utilization of high pressure ratios and elevated turbine inlet temperatures. The advanced study engines range in OPR's up to 100 and turbine rotor inlet temperatures to 3700°F. Improved component efficiencies and reduced cooling flow requirements are included in the advanced engine cycles, as well.

Ideal power performance indices for the ten production engines and the two advanced study engines have been plotted on Figures 6 and 7 relative to availability or demonstration date. As already noted, the performance of

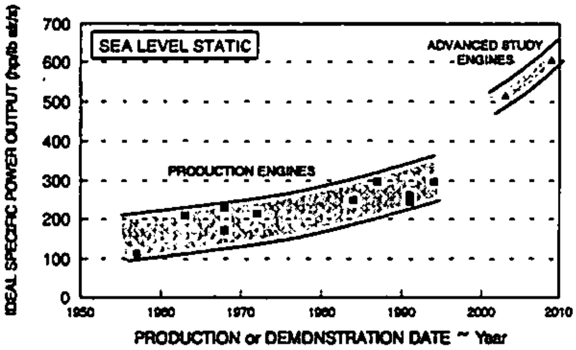

Figure 6 - Historic Trends in Ideal Specific Power

engines has risen steadily with time, with diminishing returns. The advanced engines need to provide a significant improvement in performance compared to production engines if they are to continue to impact production engine performance trends. Advanced engine demonstrators must be significantly better and show improvements at a faster rate to allow for continued improvement in future production engines. The first advanced engine is suggested to be demonstrated in the 2003 time period. It will represent a 73% increase in specific power output and a 10% improvement in power output per unit fuel flow rate.

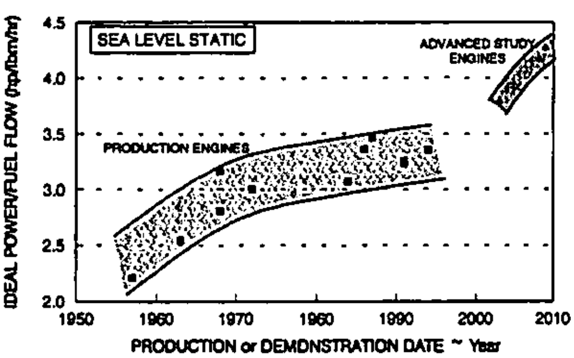

Figure 7 - Historic Trends in Ideal Power Fuel Consumption

The demonstration date of the second advanced engine is somewhat arbitrary, but the engine will provide a 103% increase in specific power output and a 23% improvement in power output per unit fuel flow rate. This represents an essentially continuous improvement relative to current production engines. The percentage increases are with respect to the best production engine shown. It should be observed that achieving an overall level of performance is the important factor, not the particular overall pressure ratio. There are other advanced cycle approaches other than the 100 OPR cycle (for example, increasing component efficiencies, reducing cooling flow, and increasing turbine inlet temperature) suggested in this analysis. But in order to achieve the improvements in performance suggested for these two technology generations, a significant level of increase in both overall pressure ratio and turbine inlet temperature will be needed.

7.0 CONCLUSIONS

The comparison approach of different turbomachinery configurations outlined in this paper has been shown to be equitable. The primary variables associated with the Brayton cycle, pressure ratio and turbine inlet temperature, are utilized to perform the analysis and comparison. With this approach, the propulsive efficiency parameters of bypass ratio/fan tip pressure ratio and nozzle expansion ratio are removed from the analysis. The methodology represents a useful way to compare various existing engine cycles and forecast desirable future cycle characteristics.

Based on the ideal power performance parameters, the gas turbine engine still has the potential for significant improvement, both in terms of power output and fuel economy. The required component cycle characteristics are challenging, indeed. But at the pressure ratio and turbine temperature levels anticipated in this study, the authors believe that the gas turbine will continue to have significant performance improvement potential in the future. The current class of land-marine engines that are adaptations of aircraft powerplants, along with recent aircraft engine developments, are paving the way. The future of gas turbine power is upward.

8.0 CONVERSION FACTORS

BTU = 1.05504 kJ
°F = 1.8°C + 32
hp = 745.7 Watts
lbm = 0.45359237 kg
°R = 1.8°K

9.0 REFERENCES

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2. Shepherd, Dennis G., "Aerospace Propulsion", American Elsevier Co., 1972, pp. 81-107