# A WORK AVAILABILITY PERSPECTIVE OF TURBOFAN ENGINE PERFORMANCE

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## Abstract

This paper presents a work availability perspective on the thermodynamic performance of the turbofan engine and contrasts this with the classic presentation, which describes performance based primarily on cycle efficiency. It is shown that the availability perspective leads to a more fundamental understanding of the basic problem, this being to maximize the conversion of work potential stored in the fuel into useful work output. The discussion specifically addresses the impact of primary turbofan cycle parameters on usage and loss of work potential. It is shown that cycle pressure ratio governs exhaust heat losses, turbine inlet temperature governs non-equilibrium combustion losses, and fan pressure ratio governs loss due to residual exhaust kinetic energy. Finally, simplified loss calculation methods applicable to any turbofan engine are presented and the method is applied to the analysis of cycle losses in the Northrop F-5E propulsion system.

## Introduction

Ever since the inception of the heat engine, the thermodynamic objectives guiding the design of prime-movers has always been clear: *to build machines with the highest possible efficiency and specific power output*. It is accurate to say that this objective continues to be the primary preoccupation in the thermodynamic design and optimization of modern gas turbine engines. As such, it is of obvious importance to have a complete understanding of the underlying principles impacting the performance of these machines.

Modern textbook-type presentations of gas turbine thermodynamic performance typically focus on the use of cycle efficiency as an overall figure of merit. This approach has proven quite useful in understanding the relationship between cycle parameters and thermodynamic performance, particularly when used in conjunction with temperature-entropy diagrams. However, the drawback to this approach is that it is based purely on conservation of energy and concentrates on accounting for the transfer of heat energy into useful work. Therefore, it gives no insight as to the efficiency in transferring *work potential* into useful work, and it is the transfer of work potential that is truly the crux of thermodynamic design. Consequently, there is a need for some means of quantifying thermodynamic performance in terms of work potential transfer, as opposed to energy transfer.

Fortunately, such a work potential figure of merit already exists and has in fact been the subject of research and theoretical development starting with the work of Carnot, and later, J.W. Gibbs. This figure of merit is presently known as availability or exergy, the theoretical underpinnings of which are today quite well developed. Exergy can be thought of as the maximum work that can be obtained in taking a substance from a given temperature, pressure, and chemical composition into a state of thermal, mechanical, and chemical equilibrium with the environment. Therefore, exergy is a measure of work potential, and exergy transfer is the metric for transfer of work potential alluded to previously. This concept is the key to enabling a description of cycle performance based on *work potential*, thus providing another point of view to augment the efficiency-based presentations of turbofan engine performance so prevalent today.

The presentation of turbofan engine performance in terms of efficiency is well-known, as evidenced by the voluminous literature available on this topic (notably the texts by Bathie,[1] Hill and Peterson,[2] and Whittle[3]). This discussion will attempt to add to current understanding by framing turbofan engine performance in terms of obtaining the maximum possible work from the work potential stored in the fuel. This description is then examined vis á vis the established efficiency-based presentation. The impact of each cycle parameter on transfer of work potential is considered separately, and both the efficiency-based and work potential-based viewpoints are discussed for each parameter. Finally, simplified methods for estimation of losses due to engine cycle impacts are presented to illustrate the ideas suggested in each section and these methods are applied to the analysis of the Northrop F-5E propulsion system as a case study.

## Classic Presentation of Turbofan Performance

The factors that impact specific power output and efficiency of a engine more than all others are the basic cycle parameters. Consequently, an understanding of the relationship between cycle parameters and

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thermodynamic performance is of prime importance. In the case of the turbofan powerplant, these parameters are overall pressure ratio (OPR), turbine inlet temperature (TIT), and fan pressure ratio (FPR). Although there are other cycle parameters such as throttle ratio, bypass ratio, and extraction ratio that are significant to determining the operation of the engine, it is the view of the authors that these parameters do not hold the same fundamental importance as OPR, TIT, and FPR. Note that for the purposes of this paper the authors will neglect the impact of component efficiencies on overall cycle performance.

As a starting point, it is useful to briefly review the way that turbofan engine performance is currently interpreted. The impact of cycle parameters on overall thermodynamic performance is commonly illustrated via a temperature-entropy (T-S) diagram. This is a very convenient means of expressing cycle performance because it is graphical and intuitive, especially since heat and work transfer interactions appear as areas bounded by the cycle processes. Consequently, the depiction of a cyclic process on a T-S diagram is essentially an expression of the first law of thermodynamics.

Cycle efficiency appears as a ratio of areas on the T-S diagram. This description of the thermodynamic cycle leads naturally to the notion that a cycle can be viewed as being analogous to a transfer function that converts heat energy of the fuel into useful work. Changes in the cycle parameters change the “gain” of the transfer function. Turbofan efficiency is in turn composed of three parts: thermal, transfer, and propulsive efficiencies, as described by Lewis.[4] *Thermal efficiency* is a metric on how efficiently the basic power cycle converts potential energy of the fuel into usable work potential, the remainder appearing as heat. *Transfer efficiency* is a measure of how efficiently the cycle power output is transferred into work on the propulsive stream passing through the engine. Finally, propulsive efficiency is a measure of how much of the work done on the propulsive stream appears as thrust work. These efficiencies are the primary metrics by which turbofan thermodynamic performance is measured, and are defined as:

$$\text{Thermal Eff.} = \eta_{th} \equiv \frac{\text{Core Avail. Work Output}}{\text{Heat Input}} \qquad (1)$$

$$\text{Transfer Eff.} = \eta_{tr} \equiv \frac{\text{Kinetic Energy Production}}{\text{Core Avail. Work Output}} \qquad (2)$$

$$\text{Propulsive Eff.} = \eta_{p} \equiv \frac{\text{Thrust Work}}{\text{Kinetic Energy Production}} \qquad (3)$$

$$\eta_{\text{overall}} = \frac{\text{Thrust Work}}{\text{Heat Input}} = \eta_{th}\eta_{tr}\eta_{p} \qquad (4)$$

The standard textbook presentation of turbofan performance focuses on how the cycle parameters impact the above efficiencies as well as specific power output. This is essentially a first-law perspective in that the focus is on accounting for the transfer of energy, as opposed to work potential. The point of this paper is to show that there is a more fundamental point of view on the nature of the relationships between cycle parameters and gas generator performance. Specifically, one could equally as well view cycle parameters in terms of their impact on work potential generated by the cycle (and loss thereof), a perspective requiring application of both the first and second laws. This is the basis of the exergy method mentioned earlier, and the point of departure for this discussion.

## Exergy as a Work Potential Figure of Merit

Exergy is a thermodynamic quantity that describes the maximum (Carnot) work obtainable in taking a substance from a prescribed temperature, pressure, and composition into thermal, mechanical, and chemical equilibrium with its environment. It is be defined as:

$$Ex \equiv H - H_{amb} - T_{amb}\left(S - S_{amb}\right) + \left(\text{Other Terms}\right) \qquad (5)$$

where H is enthalpy, S is entropy, and subscript ‘amb’ denotes ambient conditions. The other terms account for exergy transfer via kinetic energy, potential energy, electric or magnetic fields, radiation, etc. Note that while energy is a conserved quantity, exergy is *not*, and is always destroyed when entropy is produced. Note also that the exergetic content of a substance depends on the ambient environment.

For the case of calorically perfect air where chemical potential, kinetic energy, and potential energy are negligible it is a simple matter to obtain an equation for mass-specific exergy as a function of ambient conditions and gas conditions at a given engine station by noting that:

$$h - h_{amb} = c_p\left(T - T_{amb}\right) \qquad (6)$$

where h is mass-specific enthalpy and $c_p$ is the constant pressure specific heat. Using the integrated form of the second TdS relation:

$$s - s_{amb} = c_p \ln\left(T/T_{amb}\right) - R\ln\left(P/P_{amb}\right) \qquad (7)$$

where P is pressure and R is the gas constant. Substitution of Eq. 6 and Eq. 7 into Eq. 5 yields:

$$ex = c_p\left(T - T_{amb}\right) - c_p T_{amb}\ln\left(T/T_{amb}\right) + RT_{amb}\ln\left(P/P_{amb}\right) \qquad (8)$$

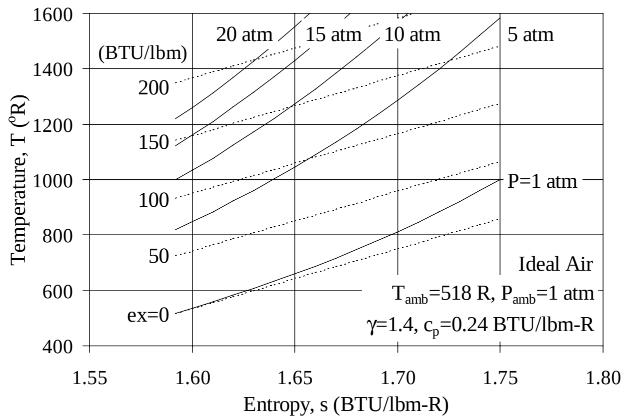


**Fig. 1: T-S Diagram Showing Contours of Constant Exergy (Dashed) and Pressure (Solid).**

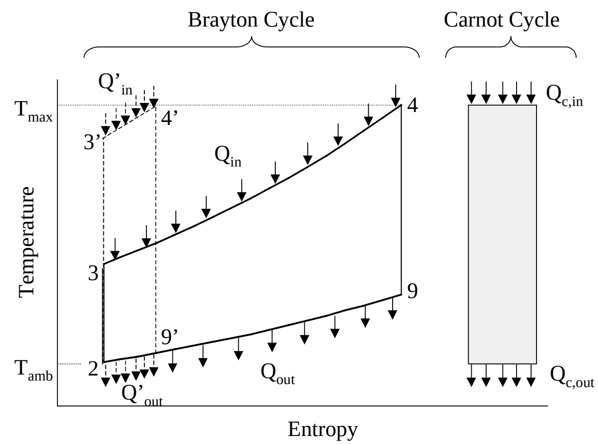


**Fig. 2: The Impact of Pressure Ratio on Thermal Efficiency, Work Output, and Exergy Loss.**

Rote application of this equation to every engine station yields the exergy at each station. Clearly, Eq. 8 is of limited value for propulsion applications where vitiation, vibrational excitation, chemical reactions, and other effects are important. Fortunately, it is relatively simple to obtain accurate estimates for flow exergy including these effects using modern software packages for evaluation of thermodynamic properties. The losses associated with each component can then be calculated based on the idea that the difference between the exergy fluxes into and out of a component must be equal to the sum of the power output and the exergy loss rate as given by:

$$\dot{E}x_{in} - \dot{E}x_{out} = \dot{W}_{out} + \dot{E}x_{Loss} \tag{9}$$

Exergy methods have been the subject of considerable development over the past several decades, and have reached a state of relative maturity in theory, if not implementation. There are a number of books describing the theoretical underpinnings of exergy in great detail, and the interested reader is referred to Bejan[5] for an excellent description of this work. Since the objective of this paper is not to give a lengthy diatribe on the theoretical basis of exergy methods, it is assumed that the reader is already familiar with these concepts. However, there is one important concept that deserves note, as it will be of use later in this discussion: the description of exergy in terms of a T-S diagram.

Contours of constant exergy appear on a T-S diagram as straight lines. For example, Fig. 1 shows isobaric (solid line) and isoexergetic (dashed line) contours for the case of ideal, calorically perfect air.[6] The contour labeled 'ex=0' indicates the locus of points that have zero work potential. A substance in a state above this contour has the potential to do work, the total exergy at a given point being proportional to the temperature and entropy of the working fluid. It is clear based on this figure that exergy is increasing as one moves upwards and to the left on the T-S diagram, and this is the desirable region if the objective is to produce work using a heat engine. Note that the zero exergy contour passes through the reference (ambient) state.

## The Impact of Engine Cycle on Work Potential

The ability to plot lines of constant exergy on a T-S diagram is particularly useful in understanding the impact of cycle parameters from a work potential point of view. This section uses this plot as a basis to examine each of the three cycle parameters individually, and compare the energy and work potential presentations. For the discussion of OPR and TIT impact on work potential, only the gas generator is considered, the presence of the fan is ignored. Note that the diagrams shown henceforth are not to scale, and are meant for illustrative purposes only. The engine station designations used herein are: 2 for engine front face, 3 for compressor discharge, 4 for turbine inlet, and 9 for nozzle exit.[‡]

**Overall Pressure Ratio.** A succinct argument illustrating the impact of cycle pressure ratio on thermal efficiency of a Brayton-cycle gas generator performance is illustrated in Fig. 2. The left side of this figure shows two cycles superimposed on a T-S diagram. One is taken to be the baseline cycle (solid), while the other features a drastically increased cycle pressure ratio (dashed). Both cycles are assumed to be operating with ideal air at the same ambient and turbine inlet temperatures, and all turbomachinery is assumed to be isentropic. Further, assume that the heat addition for this example occurs not through combustion, but rather through an imaginary heat exchanger interacting with the working fluid. Keeping in mind that the area

‡ All engine station designations and nomenclature used herein are consistent with SAE ARP 755B.

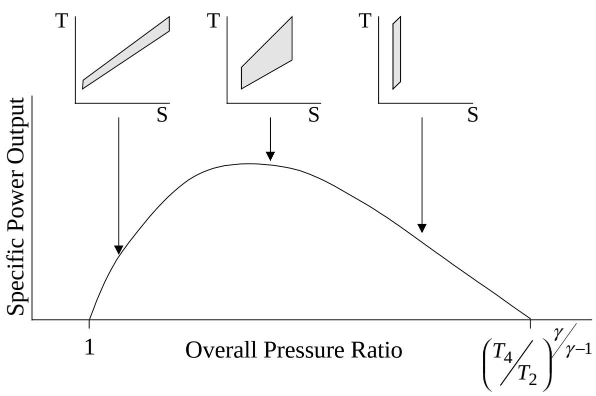


**Fig. 3: The Impact of Cycle Pressure Ratio on Specific Work Output.**

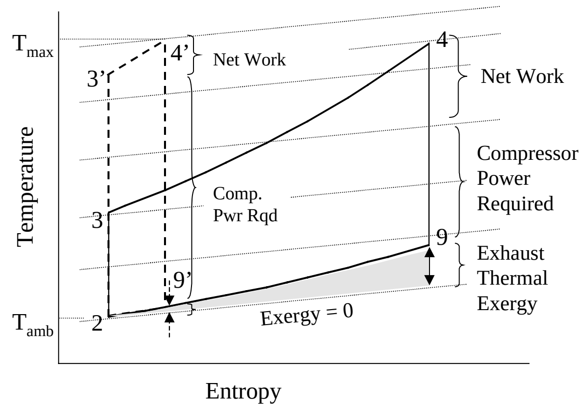


**Fig. 4: Impact of Cycle Pressure Ratio on Exhaust Residual Exergy.**

enclosed by the cycle is the specific work output, and that the area under each curve is equivalent to heat transfer, it is clear that the two cycles have vastly different thermal efficiencies. To see this, observe that thermal efficiency is equivalent to the ratio of the area enclosed by the cycle (work out) to the total area under the curve from 3-4 (heat input). In the limit as compressor discharge temperature approaches the turbine inlet temperature, the efficiency of the gas generator approaches the Carnot efficiency for a machine operating between the same temperature reservoirs (illustrated on the right). Meanwhile, the specific work output will first increase with increasing OPR, reach a maximum, and finally approach zero as the compressor discharge temperature approaches the turbine inlet temperature, as illustrated in Fig. 3.

Next, consider this same scenario from an exergy point of view. For the baseline cycle shown in Fig. 2, the exergy available at the turbine inlet is used in three ways. A portion is used to drive the compressor (for a net gain of zero exergy), while another portion is available to do work in a turbine, nozzle, or other flow device.[§] The remainder is lost out the tailpipe in the form of heat, as shown in Fig. 4. As the cycle pressure ratio increases, the portion of exergy extracted for the compressor is increased, while the work output and exhaust exergy continually decrease, with exhaust exergy loss decreasing more quickly than work output.

In Fig. 4, the distance from the exergy = 0 line to the bottom of the cycle (line 2-9) is the exergy loss due to exhaust heat. The distance from point 4 to point 9 is gross exergy available, and segment 4-9 minus segment 2-3 is equivalent to the net work available. It is easy to see from this figure that if the cycle pressure ratio is increased while holding TIT constant, the component of exergy wasted in the exhaust stream will become progressively smaller, eventually vanishing when the compressor discharge temperature (station 3) is equal to the turbine inlet temperature (station 4). In effect, increasing cycle pressure ratio causes more exergy to appear as cycle work at the expense of exhaust exergy loss. Consequently, *cycle pressure ratio governs the amount of exergy lost in the form of exhaust heat*, with increasing pressure ratio decreasing exhaust heat loss.

This observation is the fundamental difference between the first-law presentation and the exergy-based presentation. Whereas the former quantifies cycle performance in terms of heat and work interactions (i.e. efficiencies and exhaust heat rejected), the latter quantifies cycle performance in terms of *loss in the potential to do work* (exhaust work potential rejected). Consequently, one could argue that the latter view is somewhat more fundamental to the analysis of prime movers.

**Turbine Inlet Temperature.** The importance of turbine inlet temperature on specific work output and thermal efficiency can be conveniently expressed in the form of a T-S diagram, as shown in Fig. 6. This figure shows two cycles, a baseline (solid), and increased TIT (dashed) cycle. It is clear based on the figure that an increase in TIT causes a marked increase in specific work output, as evidenced by the increase in area enclosed by the cycle. In addition, it is clear that this increased work comes at the expense of thermal efficiency, as can be seen by comparing the ratios of enclosed to total area for the two cycles. Thus, based on this argument, one must conclude:

1) The primary incentive for increasing TIT is to produce an increase in specific power output and (ostensibly) an accompanying decrease in propulsion system mass, and
2) An increase in TIT should be accompanied by an increase in OPR if one wishes to maintain the same thermal efficiency.

As viewed from an exergy standpoint, the impact of TIT is somewhat different. To understand this,

[§]This portion of the work potential is termed the “available energy” or “gas horsepower,” and is discussed by Roth & Mavris.[7,8]

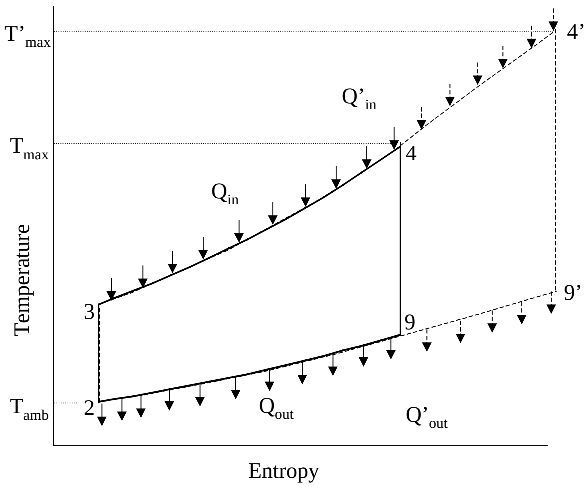


**Fig. 6: Impact of Turbine inlet Temperature on Cycle Efficiency and Specific Work Output.**

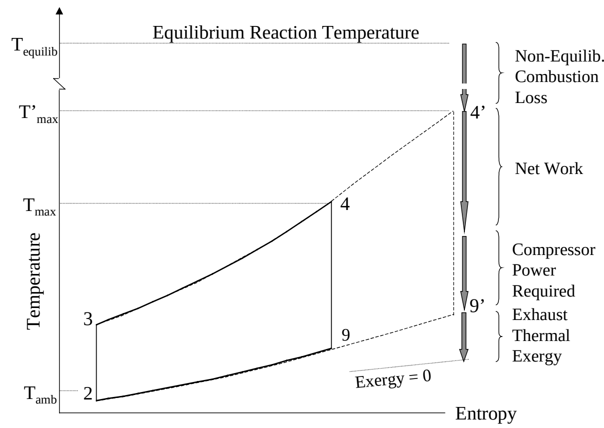


**Fig. 5: Impact of Turbine Inlet Temperature on Exergy Loss.**

consider the total exergy that is theoretically available in the fuel as compared to the actual increase in flow exergy between stations 3 and 4. It can be shown that the exergy available in the fuel is equal to the Gibbs free energy of the reaction(s) oxidizing the fuel, which is roughly equal to the fuel lower heating value.[**] For simplicity's sake, the exergy available in the fuel is approximated as the fuel heating value, meaning that nearly the entire heating value of the fuel could be converted to work, given an appropriate thermodynamic cycle. The work that would be produced by such a machine is inevitably much larger than the increase in exergy that is actually realized by the working fluid in passing from compressor discharge to turbine inlet, implying that this exergy is lost during the combustion process. The reason for this is that combustion of fuels is typically a non-equilibrium process that occurs at temperatures much lower than the equilibrium reaction temperature. Non-equilibrium processes are always accompanied by production of entropy and therefore a loss of exergy.[††] The consequence of this entropy production is a loss in exergy. As TIT is increased, the reaction temperature approaches the equilibrium reaction temperature, implying that the total exergy destruction is somewhat reduced for a Carnot cycle (though it is actually increased for the Brayton cycle, unless cycle pressure ratio is increased as well). Thus, there is a clear incentive to increase TIT, not only because it increases specific power output, but also because it leads to reduced non-equilibrium combustion losses when coupled with an increase in OPR. Consequently, one could argue that *the fundamental impact of turbine inlet temperature is to govern the loss of exergy due to non-equilibrium combustion of fuel in air*. This is in contrast to the first-law view, which emphasizes the increase in specific power output with accompanying decrease in thermal efficiency.

This idea is illustrated in Fig. 5, which depicts the same two engine cycles shown in Fig. 6, but with the addition of a equilibrium reaction temperature at some temperature higher than T4. As this figure shows, combustion at anything other than the equilibrium reaction temperature is tantamount to taking the very hot products of equilibrium combustion (primarily Carbon Dioxide and water) and diluting them via mixing with a cold stream (the Nitrogen diluent present in air) until the temperature reaches T4. Since mixing of hot and cold streams results in an increase of entropy, it also results in the destruction of work potential (exergy) in the products of combustion. Thus, the region between line segment 3-4 (or 3-4') and the equilibrium reaction temperature is effectively the result of mixing hot and cold streams. It appears as a non-equilibrium combustion loss whereby only a fraction of the exergy inherent to the fuel is actually realized as an increase in the exergy of the working fluid in the gas generator.

It is interesting to note that non-equilibrium combustion is typically the largest single source of loss in a gas turbine engine (stationary or propulsive), and

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[**]The interested reader is referred to Li[9] and Moran[10] for an in-depth discussion on calculation of fuel availability.

[††]In fact, even at stoichiometric temperatures for combustion of fuel in air, the exergy extracted from the fuel will still be much lower than the theoretical maximum. To understand this, consider the reaction mechanisms at the molecular level. This involves various species of carbon and hydrogen atoms bonding to oxygen to yield water and carbon oxides which are in the excited state, typically with an energy on the order of one electron volt. This energy is the equivalent to several thousand degrees Kelvin, much more energetic than the average gas molecule in the combustion region. These excited molecules collide with less energetic molecules and give up some of their energy in the process. The net effect is equivalent to mixing two streams of hot and cold fluid to produce a warm stream, along with an accompanying increase in entropy of the system (Ackeret, p. 85).[11]

its magnitude is usually on the same order as all other sources of loss combined. Thus, there is a large incentive to decrease the losses associated with non-equilibrium combustion. This can be done through increased TIT in conjunction with increased OPR, and is a strong justification for continued pursuit of ever higher TIT and OPR than is achievable using today's technology.

**Fan Pressure Ratio.** The fundamental significance of fan pressure ratio from a thermodynamic cycle perspective is its strong impact on specific thrust, and thus, propulsive efficiency. To understand this, consider first the case of the turbojet engine. Propulsive efficiency of a turbojet is determined by the ratio of jet exhaust velocity to flight velocity. Jet velocity is in turn determined by nozzle pressure ratio and gas temperature in the nozzle inlet. For a turbojet, the tailpipe temperature and pressure are governed by OPR and TIT. As a result, specific thrust and propulsive efficiency are a fall-out of the gas generator cycle, with increases in propulsive efficiency generally being accompanied by decreases in thermal efficiency.

*The single most important feature of the turbofan engine is that it de-couples propulsive and thermal efficiency by allowing specific thrust to be chosen independently of the gas generator cycle*. This is done by using the gas generator to drive a fan whose pressure ratio is free to be chosen to best suit a particular application. Nozzle inlet pressure and temperature for this type of engine are dominated by FPR, with the bypass ratio contributing only a second-order effect.[‡‡] Consequently FPR sets turbofan specific thrust, which is in turn a strong driver on propulsive efficiency.

It should be evident based on the previous discussion that the exhaust residual kinetic energy left behind in the jet wake is governed by FPR. Thus, *fan pressure ratio governs the exergy loss due to exhaust residual kinetic energy*. This point of view is much the same as the conventional point of view, with the primary difference being once again that the exergy point of view uses loss in work potential as a direct figure of merit rather than resorting to an efficiency.

## Brayton Cycle - Work Potential Perspective

The overall impact of each of these three cycle parameters on loss in work potential is summarized in Fig. 7. This figure shows the total work potential of the fuel being partitioned into five portions. The top region is due to non-equilibrium combustion losses, governed by TIT. The second region (above and below the Brayton cycle process) consists of losses in the form of exhaust heat, which are governed by OPR. The area inside the Brayton cycle (2-3-4-9-2) is arbitrarily divided into two regions, one being a loss due to exhaust residual kinetic energy (governed by FPR) and the other being useful thrust work produced by the propulsion system. The ratio of these two regions is proportional to the propulsive efficiency of the machine at the flight condition of interest. Finally, the bottom-most region is labeled "Carnot Loss," and is governed by the ambient temperature of the environment in which the engine operates.

Non-equilibrium combustion, exhaust heat, and exhaust residual kinetic energy constitute roughly 60% of the total loss in fuel work potential in modern propulsion systems. Viewed from this perspective, there is clearly room for continued improvements in thermodynamic performance of aircraft engines. Fortunately, these losses can be directly controlled through manipulation of the primary cycle parameters.

Carnot loss increases as ambient temperature and pressure increase. If heat could be rejected from the engine at absolute zero temperature, Carnot losses would vanish. Fortunately, Carnot losses are generally less than the previously mentioned losses, and are usually viewed as a 'sunk cost' relative to thermodynamic work potential. In effect, Carnot losses are the 'cost of doing business' in a (slightly) disordered world, and so it is not usually bookkept as a loss.

## Simplified Loss Estimation Methods

Up to this point, the fundamental relationships between losses and engine cycle parameters have been investigated in detail, but no practical means of determining the magnitude of these losses has yet been given. Fortunately, it is relatively simple to obtain

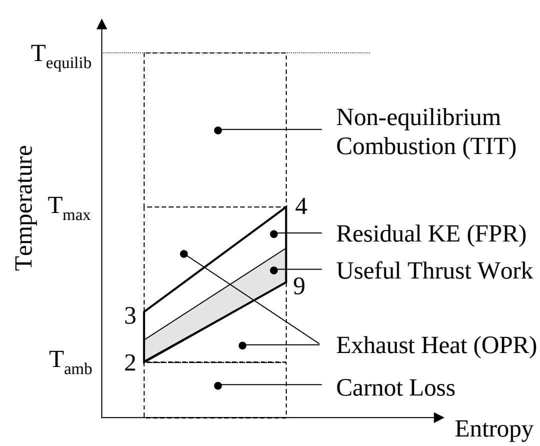


**Fig. 7: Generic Partitioning of Typical Turbofan propulsion System Losses (Assuming No Component Losses).**

[‡‡]This is the reason that the authors use FPR instead of bypass ratio as a fundamental cycle parameter for investigation in this paper. It is possible to obtain any combination (within reason) of specific thrust and bypass ratio simply by selecting an appropriate TIT. However, *there is a unique one-to-one correspondence between FPR and specific thrust that is nearly independent of all other parameters.* Consequently, FPR is fundamental to selection of specific thrust, whereas bypass ratio is not.

‘back of the envelope’ estimates of the three primary loss mechanisms using only a few simple equations. The losses associated with each of these various regions in Fig. 7 can be closely approximated for most applications using the exergy equation for ideal, calorically perfect gasses, given by equation 8.

To estimate the flow-specific loss in work potential due to non-equilibrium combustion, one need only note:

$$\text{Loss}_{\text{NE}} = ex_{\text{fuel}} - (ex_4 - ex_3) \approx q_{in} - ex_4 + ex_3 \qquad (10)$$

where station 3 is compressor discharge, station 4 is turbine inlet, and $q_{in}$ is the flow-specific heat input of the fuel. Therefore, one need only use equation 8 in conjunction with known cycle data to evaluate the total exergy flux at stations 3 and 4. The loss due to non-equilibrium combustion is then simply the difference between the exergy flux entering the combustor (in the form of compressor discharge flow and fuel) and that leaving (hot products of combustion).

The loss due to exhaust heat is readily estimated by evaluating equation 8 at the exhaust gas temperature and atmospheric pressure. Loss due to residual kinetic energy in the exhaust can be evaluated in the conventional manner by calculating the difference between exhaust kinetic energy (in the vehicle-fixed reference frame) and thrust work produced by the engine.

## Detailed Loss Estimation Methods

This section describes the basic method necessary to accurately calculate loss of thermodynamic work potential in practical propulsion engineering problems. This method is then applied to the propulsion system of the Northrop F-5E as a case study. *The result is the creation of a thermodynamic ‘loss deck’ that describes the partitioning of work potential usage (and destruction) in the F-5E propulsion system as a function of vehicle flight condition and engine power setting*.

**Analysis Method.** The basic analysis method used to create a detailed propulsion loss deck is illustrated in Fig. 8. First, a cycle model is used to calculate mass flow rate, temperature, pressure, and fuel-air ratio at every engine flow station for every flight condition and power setting. Next, the uninstalled propulsion data calculated from the cycle analysis is corrected for installation effects. This data is then sent to a postprocessor, which calculates thermodynamic work potential at every station for all flight conditions and power settings.

Since this type of loss analysis is hardly standard in modern propulsion system analysis, there is no ready-made postprocessor that can be used to calculate work potential based on the cycle analysis results. Therefore, the cycle data postprocessor used herein was created “from scratch” using standard equations to estimate work potential at every flow station and all flight conditions. For the current work, a loss analysis script was implemented in MATLAB such that it can process a text file containing thermodynamic data and yield an output file containing the original thermodynamic data with work potential data appended to it.

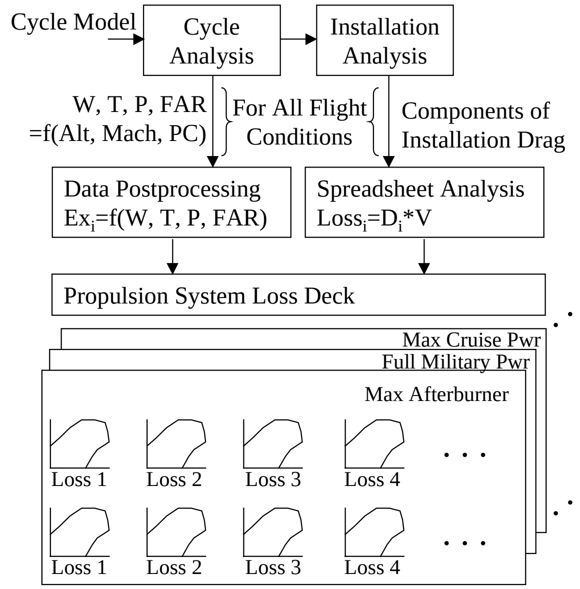

**Fig. 8: Analysis Procedure for Construction of Propulsion System Loss Decks.**

This data is then imported into a spreadsheet and manipulated to obtain thermodynamic loss attributable to each component as a function of flight condition and power setting. In addition, installation drags calculated from the installation corrections are imported into this same spreadsheet and used to calculate loss in work potential due to propulsion system-chargeable drag. Finally, these various sources of loss are assembled into a complete loss deck which completely describes the usage (or destruction) of work potential in the propulsion system at every flight condition and power setting.

**Case Study: J85-GE-21/F-5E Exergy Loss Deck.** To begin, consider a loss deck for loss in exergy (per engine) as a function of flight condition and power setting. The basic tools used to estimate exergy loss for the F-5E are the definition of exergy, the exergy “conservation” equation, and a NEPP cycle model for the J85 engine.[6,12] Exergy at each flight condition is calculated via a MATLAB function that returns exergy given pressure, temperature, fuel-air ratio, ambient pressure, and ambient temperature. This analysis results in a tabular listing for exergy loss for all loss mechanisms, flight conditions, and power settings.

This table of loss data is quite extensive, typically several hundred kilobytes. It would be impractical and not particularly useful to display this data in tabular form, so it is instead displayed in the form of “loss envelopes." These loss envelopes are a graphical and intuitive way to display loss data and are similar to standard "flight envelopes" used in vehicle performance analysis, except that loss envelopes show contours of constant thermodynamic loss as opposed to contours of constant vehicle performance.

Since the objective of this paper is to illustrate the relationships between cycle parameters and losses, only those losses attributable to the thermodynamic cycle of the J85-GE-21 engine are shown. These include exergy destruction due to non-equilibrium combustion, exhaust residual heat, and exhaust residual kinetic energy. Note that exergy losses due to component efficiency, installation drags, engine shaft power take-off, etc. can and have been calculated in the same way as the cycle losses using the method shown in Fig. 8. However, detailed analysis of exergy loss due to component inefficiency and installation effects is beyond the scope of this paper. The reader is instead referred to Ref. 6 for further details of component loss calculations.

The results from an exergy analysis of the F-5E propulsion system are shown in Fig. 9. These four panels collectively show the cycle losses due to non-equilibrium combustion in the combustor and afterburner, exhaust heat, and exhaust residual kinetic energy for maximum afterburner operation of a single J85 engine installation. Exergy losses are expressed in terms of horsepower, in deference to its widespread use as a measure of power output for prime movers.

Note that the general trends in all four panels are very similar, with cycle losses being a strong function of dynamic pressure. Also, the contours in all four panels begin to roll off at roughly Mach 1.5 due to engine performance limits (primarily T3, T4, and mechanical speed limits).

It is clear from these plots that non-equilibrium combustion and exhaust heat rejection are the dominant sources of loss at full-power. Both are roughly four times as large as non-equilibrium losses in the combustor and exhaust residual kinetic energy losses.

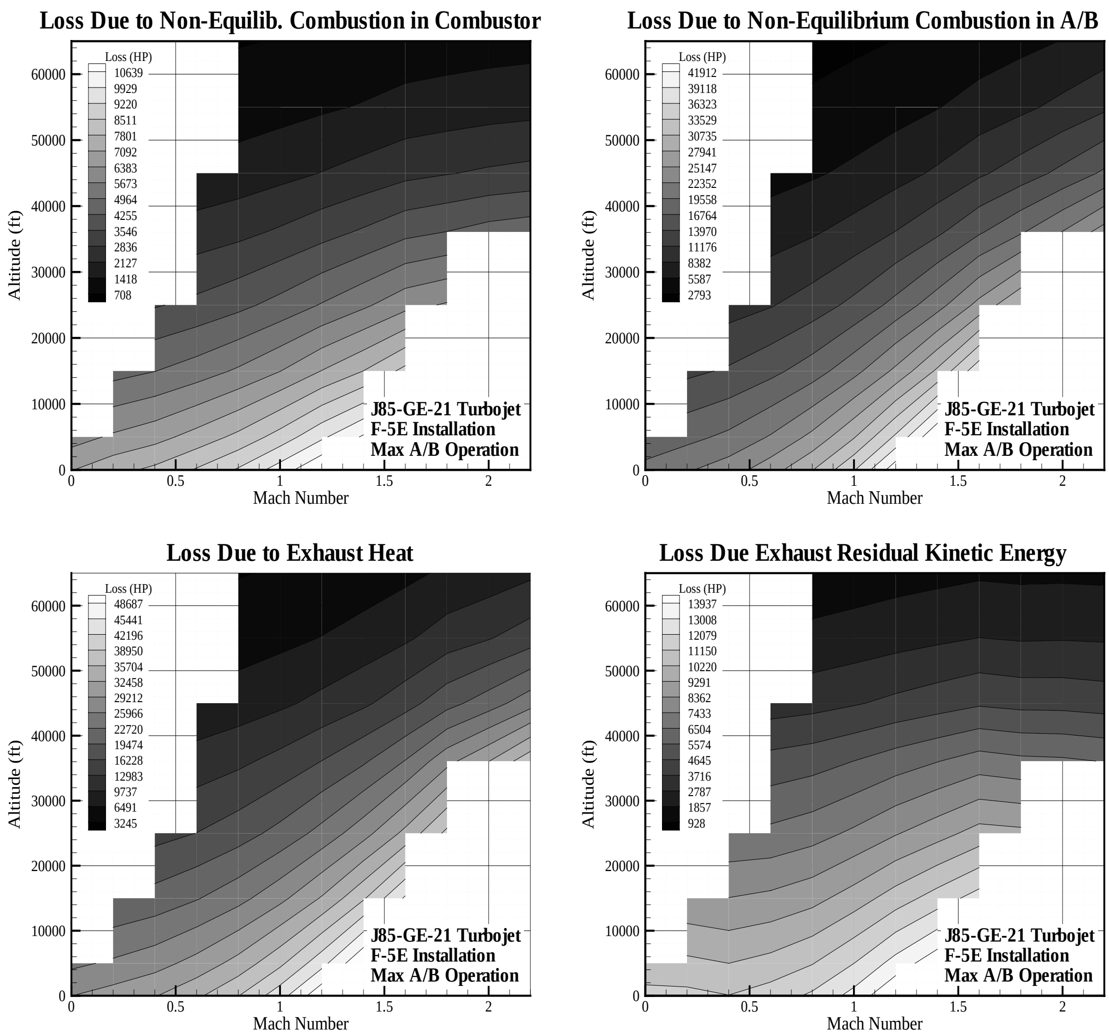


**Fig. 9: Exergy Loss Due to Engine Cycle (J85-GE-21 in F-5E Installation, Maximum Afterburner).**

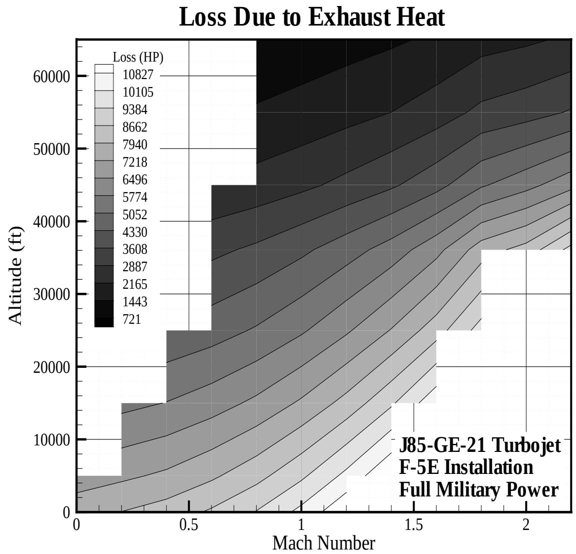


**Fig. 10: Exergy Loss Due to Exhaust Heat (J85-GE-21, Dry).**

Although the loss envelopes shown in Fig. 9 are for maximum afterburner operation, plots for other power conditions are very similar with a few exceptions. Clearly, in non-afterburning operation, the afterburner combustion inefficiency losses would be zero. Additionally, loss due to exhaust residual heat is greatly reduced when the afterburner is turned off, as evidenced in Fig. 10. Note that this plot shows that exergy loss due to exhaust heat rejection is roughly equal to the combustor non-eq. losses during dry operation. Also, since specific thrust is much lower for non-afterburning operation, one would expect that the exhaust residual kinetic energy losses would also be much lower (i.e. propulsive efficiency is higher). Since the afterburner does not effect the operation of the gas generator, there is no difference between maximum afterburner and full power operation for non-equilibrium combustion losses in the combustor.

Finally, total thrust work for a single J85-GE-21 in the F-5E installation (for maximum afterburner operation) is shown in Fig. 11. Note that thrust work is also strongly driven by dynamic pressure and has a marked roll-off at roughly Mach 1.5. It is clearly evident by comparing Fig. 11 to Fig. 9 that the thrust work produced is a relatively small percentage of total consumption of fuel work potential. In fact, for most full-afterburner flight conditions the thrust work produced is approximately 11% of total fuel exergy content. The remaining exergy is lost in the form of non-equilibrium combustion in the combustor (7%), non-equilibrium combustion in the afterburner (30%), exhaust heat rejection (34%), residual kinetic energy (10%), and component losses (8%). Since the first step in conquering losses is to know their magnitude and location, the information provided in loss decks of this sort can provide great insight to this end.

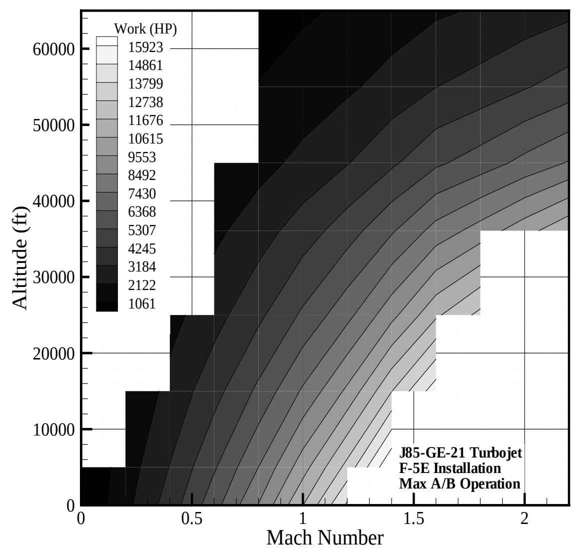


**Fig. 11: Total Thrust Work as a Function of Flight Condition (J85-GE-21 in F-5E Installation).**

## Conclusions

The objective of this paper has been to point out the relationships between the fundamental cycle parameters relevant to a turbofan engine and their corresponding impact on loss in work potential. It was shown that each cycle parameter has a distinct and unique impact on loss in work potential, which can be summarized as:

1) Overall pressure ratio governs exergy loss due to exhaust residual heat.
2) Turbine inlet temperature (in concert with OPR) governs exergy is loss due to non-equilibrium combustion.
3) For turbofan engines, fan pressure ratio governs exergy loss due to exhaust residual kinetic energy.

These three sources of loss (non-equilibrium combustion, exhaust heat, and exhaust residual kinetic energy) are by far the dominant sources of loss in modern turbofan engines today. Consequently there is ample justification (from a thermodynamic point of view) for current research directed towards increasing TIT and OPR while lowering FPR in the next generation of commercial turbofan engines.

Finally, it was shown that the efficiency-based presentation of the impact that TIT has on overall engine performance is misleading and gives no indication of the true magnitude of loss occurring due to TIT. An exergy-based presentation of turbofan engine performance has no need to measure losses in terms of efficiency, but rather measures losses directly as a reduction in work potential. It is therefore more attuned to the fundamental objectives in thermodynamic design of prime movers, that being to maximize work produced from a given fuel resource.

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