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A Method for Comprehensive Evaluation of Propulsion System Thermodynamic Performance and Loss

Dr. Bryce Roth*
Georgia Institute of Technology, Atlanta, GA 30332-0150
www.asdl.gatech.edu

Abstract

This paper develops a method to analyze usage and loss of thermodynamic work potential in vehicle propulsion systems. This method is then demonstrated on the Northrop F-5E propulsion system. The result is a thermodynamic ‘loss deck’ describing the partitioning of work potential usage (and loss) as a function of vehicle flight condition and engine power setting. Specifically, three loss deck formulations are demonstrated for the F-5E propulsion system: exergy, gas horsepower, and thrust work potential. Finally, these three loss decks are compared and contrasted to show their relative merits for propulsion system design and engine/airframe matching applications.

Introduction

There is considerable interest within the aerospace propulsion community in developing new approaches to propulsion system analysis based on the concept of thermodynamic work potential. The fundamental premise is that every substance has a well-defined upper limit on the work that can be obtained in bringing it into equilibrium with its environment. For instance, fuel has a well-defined work potential stored within its chemical bonds. The propulsion system’s fundamental function is to release the work potential stored in the fuel and convert it into useful thrust work. It is this usage and loss of thermodynamic work potential that is at the crux of aerothermodynamic design of prime movers.

It therefore follows that these ideas can be used as the basis for the development of a comprehensive method for analyzing and tracking the usage and loss of work potential in a propulsion system. This is useful as a guide to determine the relative magnitude of propulsion system losses and can be used to gain insight into the engine-airframe matching process.

Although the basic theory is relatively well-developed, it has yet to be implemented as part of a practical engineering analysis. The purpose of this paper is to develop a propulsion system loss analysis method suitable for industrial application and demonstrate its application on a problem of practical interest. The demonstration case is the Northrop F-5E propulsion system, which was selected because it has a large flight envelope with well-known performance and therefore makes a good point of validation.

This paper will begin with a general overview of the analysis process and models used to calculate propulsion system “loss decks.” The performance models discussed in Ref. 1 are used as a basis for constructing several models that describe instantaneous propulsion system loss as a function of flight condition and power setting. These models are based on the concepts of exergy, gas horsepower, and thrust work potential, and are compared to illustrate the differences between the various figures of merit (FoM).

Background

If one surveys current literature, it is apparent that the basic theory needed to perform work potential analysis has already been developed (or is imminent). Much of the general framework has been developed by Bejan,[2,3,4] who has contributed greatly towards the integration of work potential concepts with classical disciplines such as heat transfer and fluid mechanics. He has also heightened general awareness of work potential concepts and how they can be applied to obtain greater insight than is otherwise possible.

Recent research has focused on developing work potential methods specially tailored for application to aerospace propulsion. Notably, Curran[5] was one of the first to develop and articulate thrust work-based figures of merit. Riggins[6] has continued to pioneer much of the basic theory and ideas needed to apply these concepts to propulsion system analysis. Roth[7,8] has contributed towards the application of these ideas as a unifying figure of merit for all vehicle systems, not only propulsion systems.

This paper presumes a degree of familiarity on the part of the reader with the concept of thermodynamic work potential, particularly with exergy, gas horsepower, and thrust work potential. Briefly, exergy is a thermodynamic state variable defined as the maximum work that could be obtained from a substance in taking it into equilibrium with its environment. Gas horsepower is a special case of exergy in which only expansion work (as in a turbine) is presumed to be available. Thrust work potential is a special case of gas horsepower that measures the maximum possible thrust work obtainable via expansion in a thrust nozzle at a given vehicle flight velocity. Each is a figure of merit for measuring propulsion system performance, as described in Ref. 7.

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[*] Research Engineer, Aerospace Systems Design Laboratory (ASDL), Georgia Tech, Member, AIAA.

These FoM will be used to describe all sources of work potential usage and loss in a propulsion system. For the purposes of this paper, these results are presented in the form of “loss decks.” *A loss deck is defined as a comprehensive representation of propulsion system performance and loss as a function of flight condition and throttle setting*. An “engine deck” in the conventional sense is a representation of fuel flow and engine thrust as a function of flight condition and throttle setting. A loss deck is therefore a superset of the conventional engine decks used today.

Analysis Method

The basic analysis method used to create propulsion system “loss decks” is illustrated in Fig. 1. First, a cycle model is used to calculate uninstalled cycle data (mass flow rate, temperature, pressure, fuel-air ratio, etc. at every engine flow station) for every flight condition and power code (PC). Next, the uninstalled cycle data is corrected for installation effects. These first two steps are standard analysis methods in widespread use today. The new feature added to the analysis process is a post-processing step wherein the cycle analysis and installation results are used in conjunction with the work potential models to calculate the flow and loss of work potential within the propulsion system. This is accomplished by calculating thermodynamic work potential at every engine station for all flight conditions and power settings.[†]

Work potential at each flight condition is calculated in a manner similar to the example given for the J-79 turbojet engine in Ref. 7. This analysis results in a tabular listing for work potential loss due to every loss mechanism for every flight condition, and all 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,” which are nothing more than contour plots of loss as a function of flight condition. 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 type of loss analysis conducted in this paper has never been applied to propulsion system analysis before, there was no ready-made postprocessor that could be used to calculate work potential based on the cycle analysis results. Therefore, the cycle data postprocessor had to be created “from scratch” using the models given in Ref. 1 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.

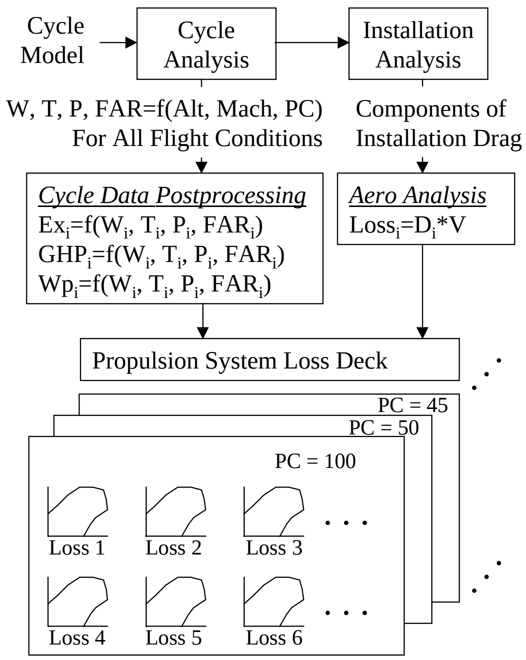


Fig. 1 Analysis Procedure for Construction of F-5E Propulsion System Loss Decks.

This data is then manipulated to obtain thermodynamic loss attributable to each component as a function of flight condition and power setting. Installation corrections are then estimated based on the airframe installation 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.

Application to the Northrop F-5E Propulsion System

The basic tools used to create loss decks for the F-5E are the cycle data postprocessor described previously, a cycle model for the J85 engine, and an installation model for the F-5E. A schematic diagram of the cycle model enumerating the various sources of loss is shown in Fig. 2.

There was no ready-made J85 cycle model available for use in this investigation, so considerable effort was exerted to create a cycle model for this work. The model set-up, governing control laws, and assumptions are discussed in Ref. 8.

[†] Note from Fig. 1 that if mass flow rate, temperature, pressure, and fuel-air ratio are known at any given engine station, it is possible to calculate work potential flux.

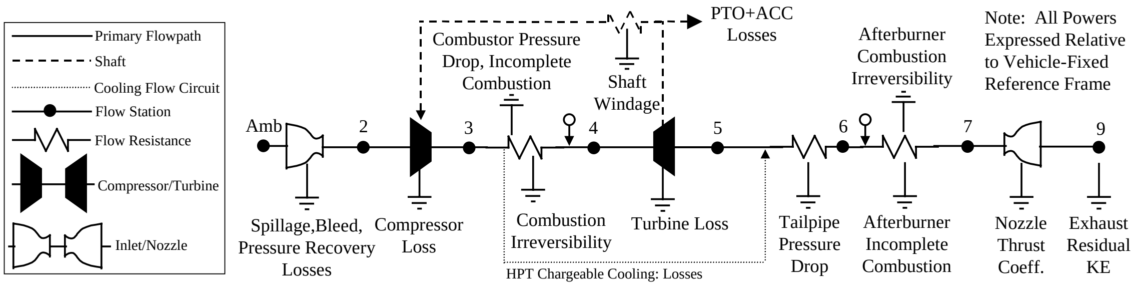


Fig. 2 Schematic Diagram of J85-GE-21 Cycle Model and Losses.

The primary cycle analysis tool used herein is the NASA Engine Performance Program (NEPP99),[9] which was developed and is maintained by NASA Glenn Research Center. The primary tool used to estimate installation losses for the F-5E propulsion system is the INSTAL analysis code.[10] Typical installed thrust work for a single J85-GE-21 in the F-5E installation estimated using the aforementioned model is shown in Fig. 3. Note that thrust work is strongly driven by dynamic pressure, and that maximum thrust work output in the envelope is roughly 15,000 HP per engine.

Exergy Model

The exergy loss envelopes presented herein for the F-5E propulsion system are divided into two general categories: losses attributable to the thermodynamic cycle of the engine and losses due to component performance. Cycle losses include exergy destruction due to non-equilibrium combustion, exhaust residual heat, and exhaust residual kinetic energy. As discussed in Ref. 11, these losses are driven by TIT, OPR, and FPR,[‡] respectively.

Fig. 4 shows engine cycle exergy losses in the F-5E propulsion system at maximum afterburner in the form of 'loss envelopes.' 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. It is clear that cycle losses are a strong function of dynamic pressure and are generally greater than all other sources of exergy loss combined. Note that the scales of each panel are adjusted such that an appropriate number of contours appear on the plot, but the scales have different ranges. For instance the largest exhaust heat loss appearing in the flight envelope is on the order of 50,000 HP, while non-equilibrium combustion loss in the combustor is on the order of 10,000 HP. Recall from the thrust work plot that the magnitude of thrust work was of the same order of magnitude as each individual cycle loss. Therefore, the cycle exergy losses are collectively 7 to 8 times the total thrust work output of the engine. If the engine is operated a full military power (non-afterburning), the non-equilibrium combustion losses in the afterburner vanish, and the exhaust heat loss is greatly reduced, as shown in Fig. 5. In this case, the relative proportion of cycle losses is considerably reduced in relation to total power output. Consequently, overall propulsion system efficiency increases considerably.

Component losses are defined as those due to component imperfections. Exergy losses in this category tend to be smaller than the cycle losses, but are more numerous. They are significant because most component losses are avoidable in that the component designer can usually make component modifications to reduce or eliminate them. On the other hand, cycle losses are fundamental to the basic engine cycle and are therefore difficult or impossible to eliminate entirely, especially from the component designer's point of view, where engine cycle is dictated by factors external to the component's design. The component-wise exergy loss due to component inefficiencies is shown in Fig. 6 and Fig. 7. These plots show that exergy loss in most engine components is strongly driven by dynamic pressure (with the exception of accessories PTO/Bearing friction).

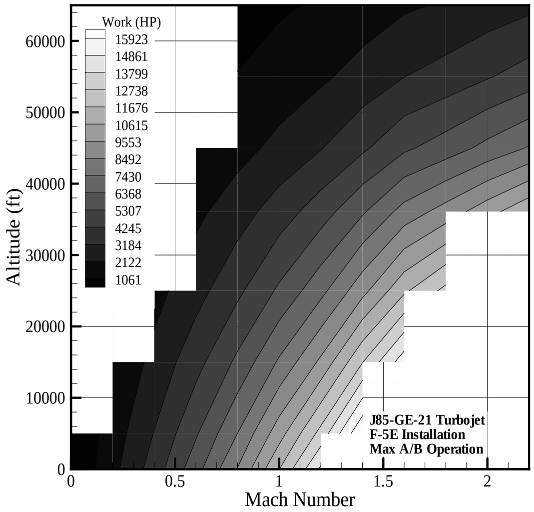


Fig. 3 Total Thrust Work as a Function of Flight Condition (J85-GE-21 in F-5E Installation).

[‡] The equivalent of fan pressure ratio for a turbojet engine is engine pressure ratio (EPR).

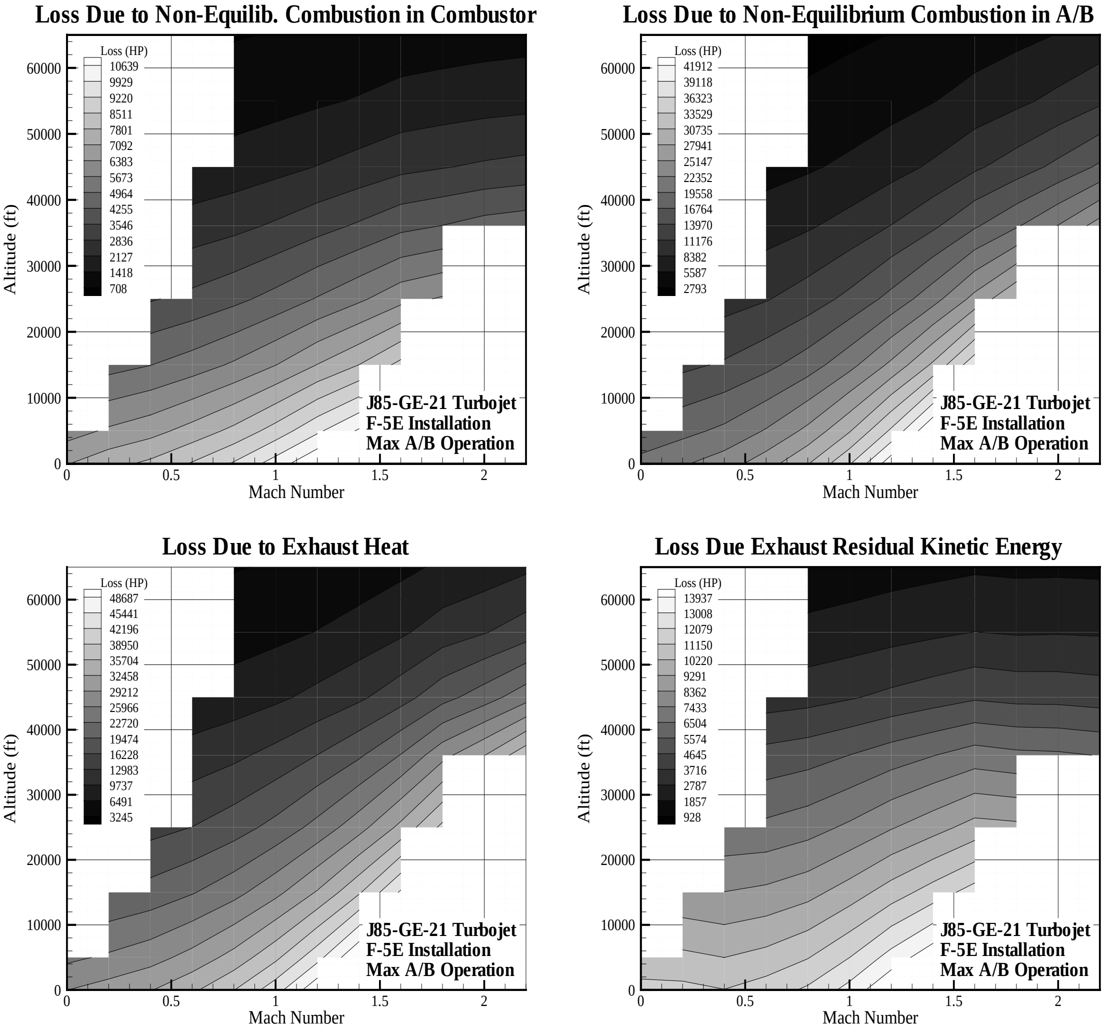


Fig. 4 Exergy Loss Due to Engine Cycle (J85-GE-21 in F-5E Installation).

One interesting feature of these plots is the behavior of inlet pressure recovery loss at low flight Mach number. As can be seen from the loss envelope, losses due to pressure recovery actually increase for very low Mach numbers because the inlet is acting as a constriction that impedes the flow of air into the engine. For the F-5E propulsion system, this loss is partially alleviated using auxiliary inlet (blow in) doors to increase the effective inlet capture area. Another interesting feature of these plots is the behavior of accessories PTO and bearing friction losses throughout the flight envelope. Note that the contours show a discontinuity at 36,089 ft (the tropopause) such that PTO/bearing losses are a function only of Mach number above this altitude. These losses are directly proportional to shaft speed, and this trend is typical for jet engines.

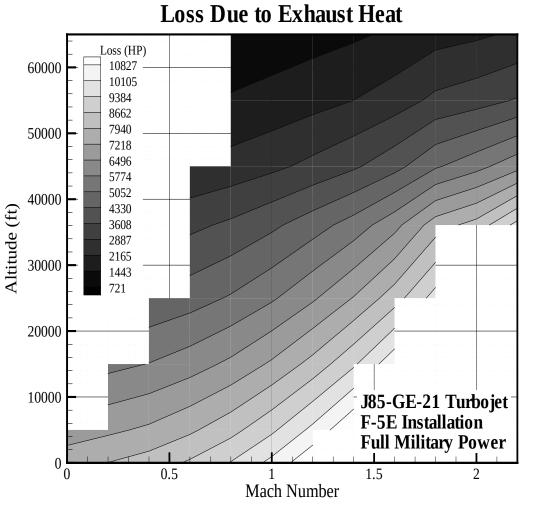


Fig. 5 Exergy Loss Due to Exhaust Heat (J85-GE-21, Dry).

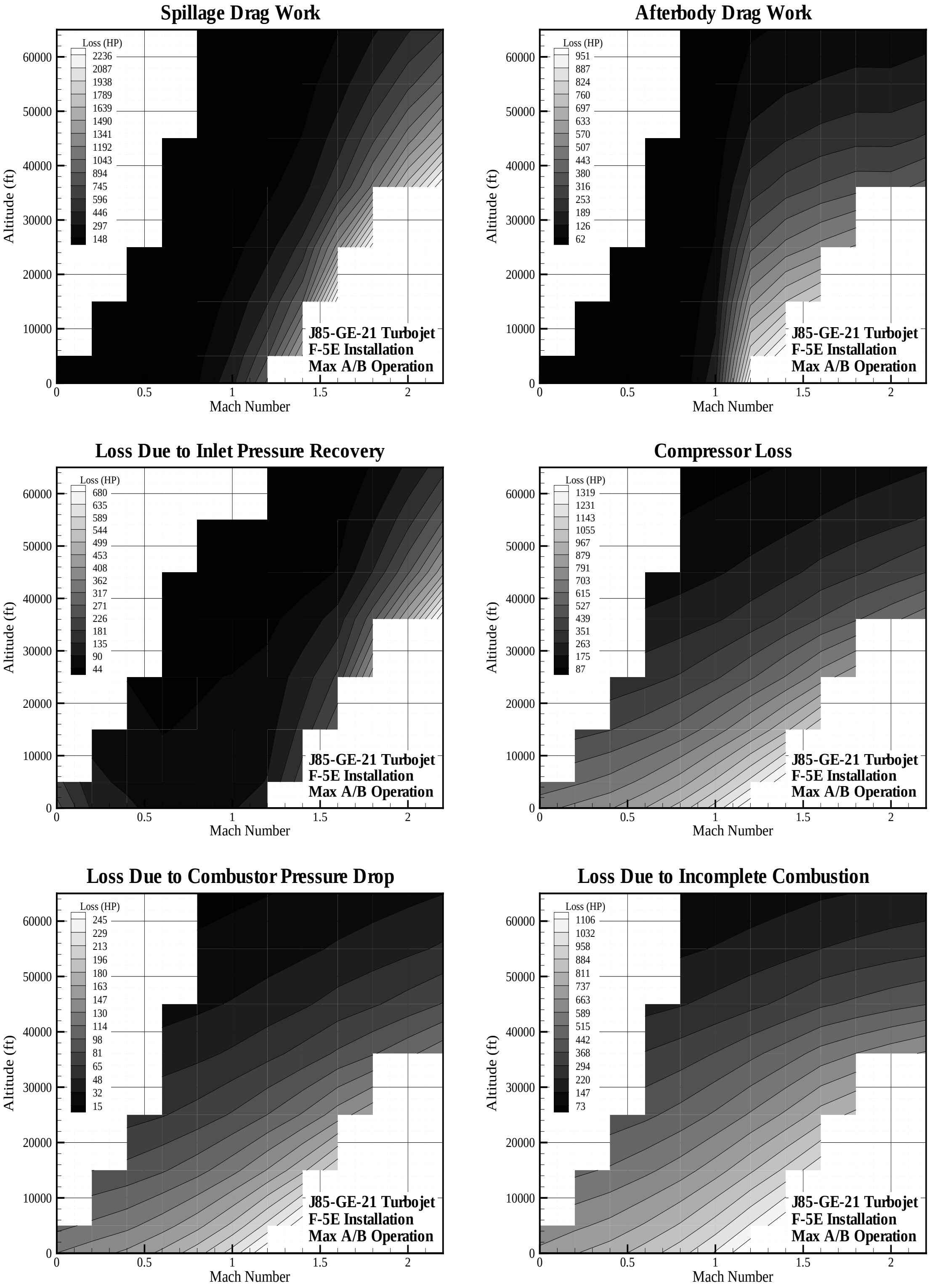


Fig. 6 Exergy Loss Due to Component Inefficiencies (J85-GE-21 in F-5E Installation).

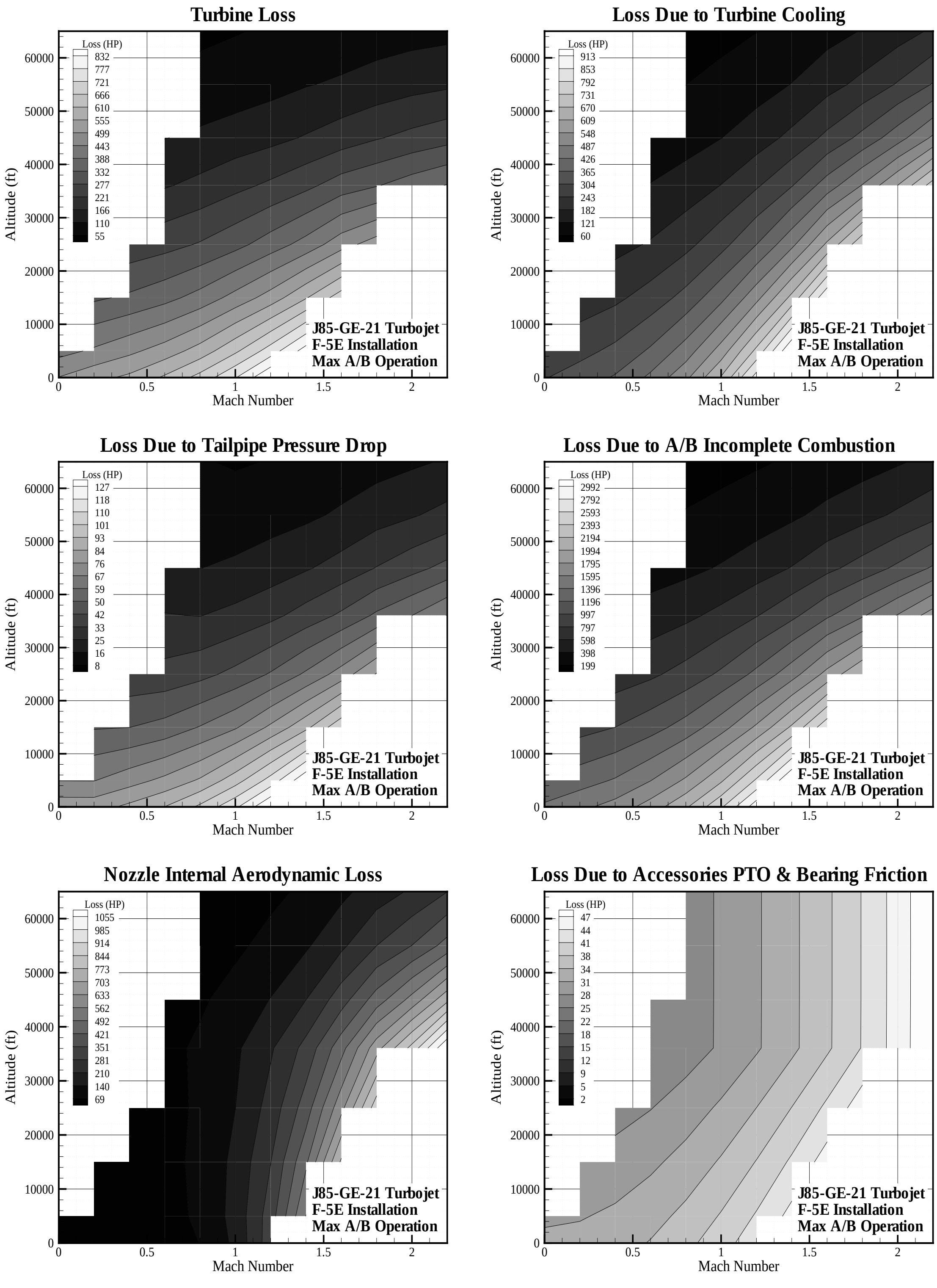


Fig. 7 Exergy Loss Due to Component Inefficiencies (J85-GE-21 in F-5E Installation, Concluded).

One feature of particular note is the exergy loss due to inlet bleed/spillage drag and the exergy loss due to nozzle afterbody drag. Both are defined by the drag force times the flight velocity of the aircraft, and are therefore invariant when viewed from an exergy, gas horsepower, or thrust work potential perspective. The reason for this is that both are measured in terms of thrust work, as opposed to work potential. These two panels will therefore be omitted in the presentation of the gas horsepower and thrust work potential loss decks in subsequent sections.

Although the loss envelopes shown in these figures are for maximum afterburner operation, plots for other power conditions are very similar with a few exceptions. In non-afterburning operation, there are no afterburner combustion losses. Additionally, loss due to exhaust residual heat is greatly reduced when the afterburner is turned off, as evidenced in Fig. 5. Also, since specific thrust is much lower for non-afterburning operation, one would expect that the losses due to exhaust residual kinetic energy would also be much lower (i.e. propulsive efficiency is higher). Finally, one would expect the nozzle losses to be lower for dry operation as compared to afterburning operation. However, since the afterburner does not effect the operation of the gas generator, there is no difference between maximum afterburner and full power operation for all components upstream of the afterburner. The loss envelopes for all upstream components are therefore the same between full military and maximum afterburning operation.

Gas Horsepower Model

Another loss figure of merit that can be used to measure the loss in work potential for the F-5E propulsion system is gas horsepower. The basic tools used to estimate loss envelopes for gas horsepower are again the definitions and equations for gas horsepower given in Ref. 1. In general, this is a very simple and straightforward process of applying the gas horsepower conservation equation. It can be shown that the loss of gas horsepower inside a component is simply equal to the sum of gas horsepower streams entering the

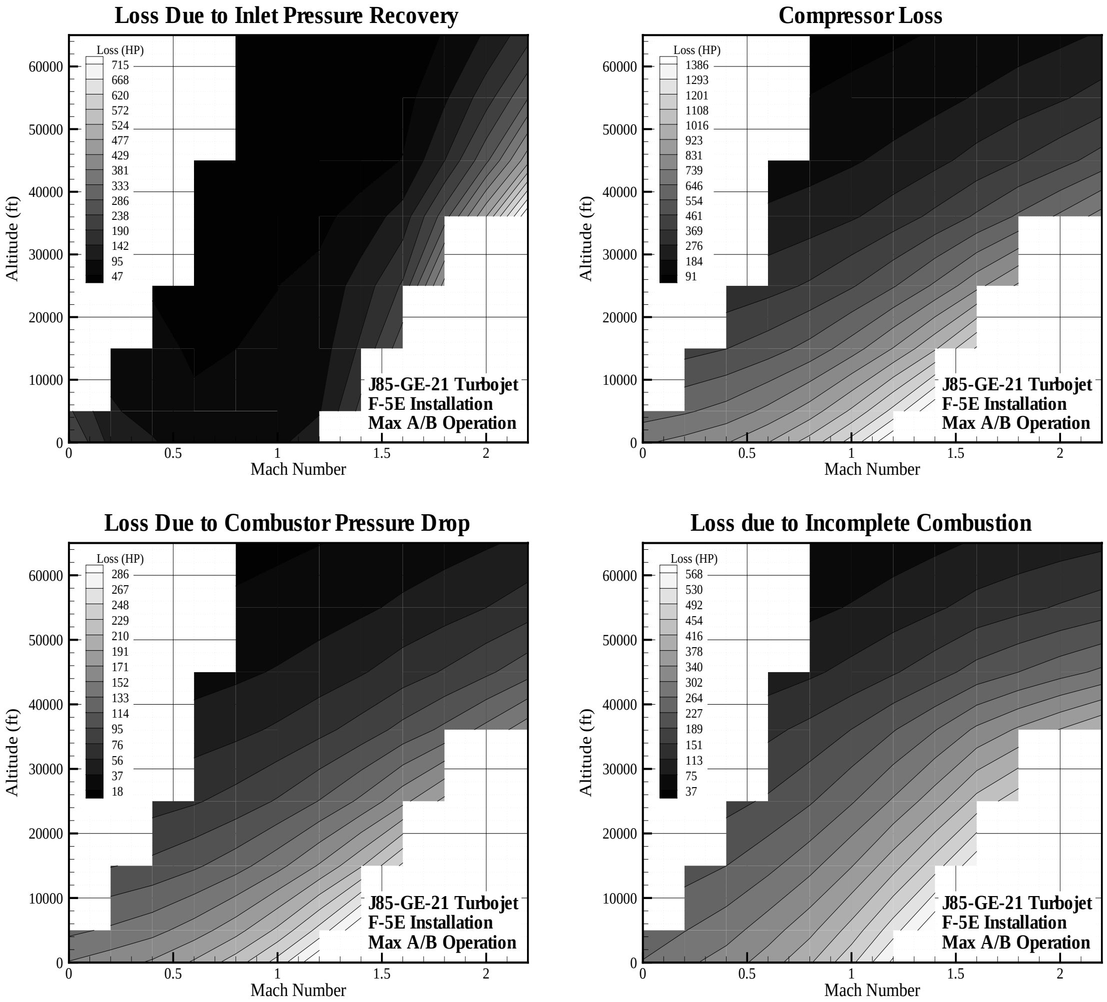
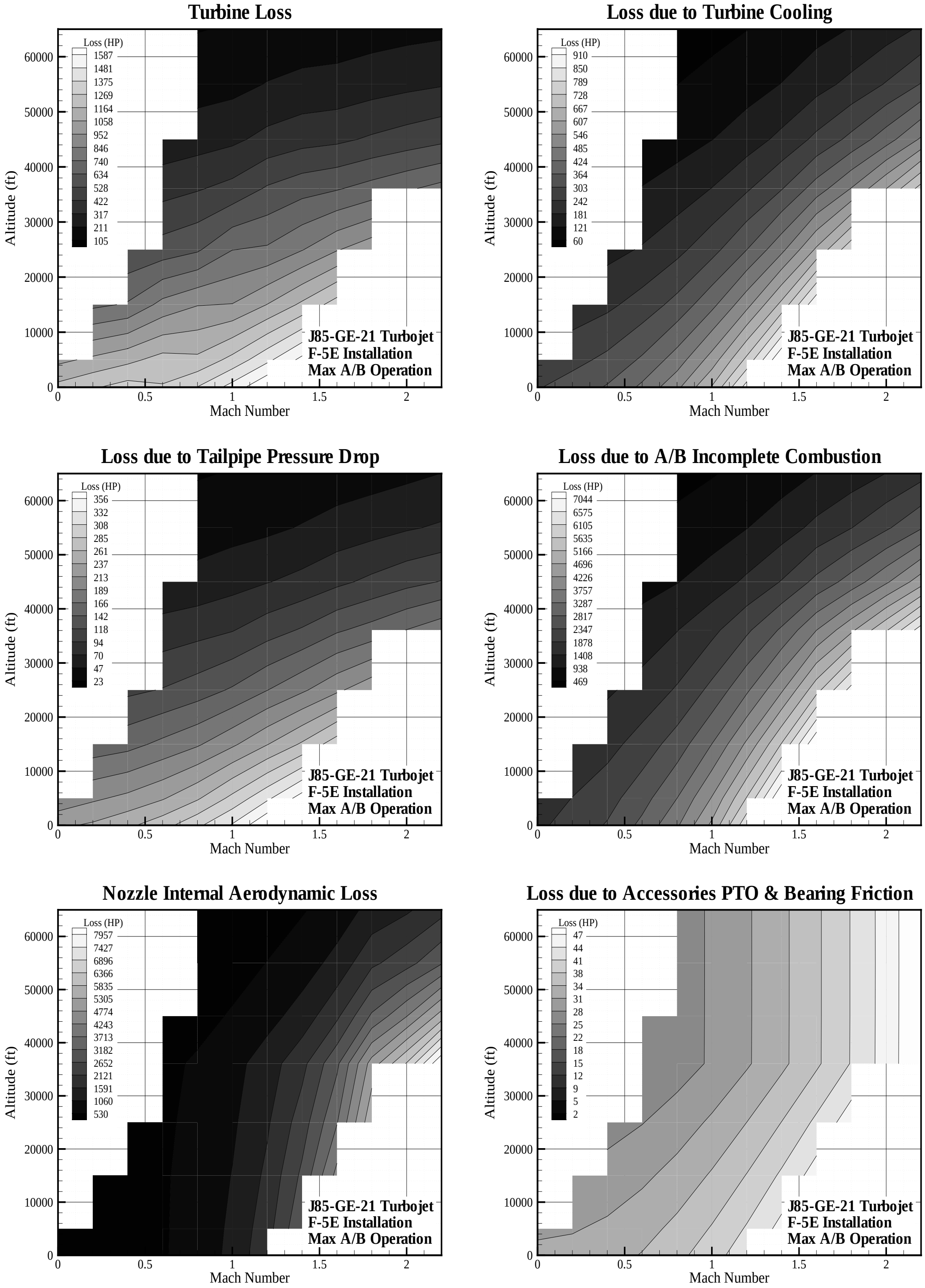


Fig. 8 Gas Horsepower Loss Due to Component Inefficiencies (J85-GE-21/F-5E Inst'ln).



Turbine Loss

Loss due to Turbine Cooling

Loss due to Tailpipe Pressure Drop

Loss due to A/B Incomplete Combustion

Nozzle Internal Aerodynamic Loss

Loss due to Accessories PTO & Bearing Friction

Fig. 9 Gas Horsepower Loss Due to Component Inefficiency (J85-GE-21/F-5E Inst'ln, Concl.).

component minus the sum of gas horsepower streams leaving the component. The only complication to the loss analysis is when there are two loss mechanisms occurring simultaneously in the same component. An example of this is the simultaneous pressure drop and combustion efficiency losses that occur in the combustor. Calculation of the exact magnitudes of these two losses would require detailed knowledge of the flowfield inside the combustor. However, this is not practical for preliminary-level design analysis, so the loss analysis process is simplified by breaking it into two discrete processes. For the present work, it is assumed that the combustor pressure drop occurs first, before any heat addition. The loss due to this mechanism can easily be calculated using the definition of gas horsepower. Next, heat is assumed to be added at constant pressure via the combustion process, and loss in gas horsepower is then estimated using the definition of gas horsepower, as was done for the pressure drop.

Gas horsepower loss due to the engine cycle is significantly different than was the case for exergy loss. This is because irreversible combustion and exhaust heat are not counted as a loss in gas horsepower because neither can be used to produce work via isentropic expansion. However, exhaust residual kinetic energy is a loss in gas horsepower, and is identical to the contour plot shown in Fig. 4.

A complete description of gas horsepower loss per engine due to component inefficiencies is given in Fig. 8 and Fig. 9 (with the exception of inlet spillage/bleed drag work and afterbody drag work). Not surprisingly, these plots show that total loss in gas horsepower is strongly driven by total engine airflow (and dynamic pressure) for most sources of loss. The largest contributors to gas horsepower loss are afterburner combustion efficiency and nozzle internal aerodynamic losses. Note that virtually all sources of loss are in the 500+ horsepower class, with the exception of accessories/bearing friction losses. The dominant gas horsepower loss is exhaust residual kinetic energy, with nozzle thrust coefficient and afterburner incomplete combustion a distant second and third, respectively.

Thrust Work Potential Model

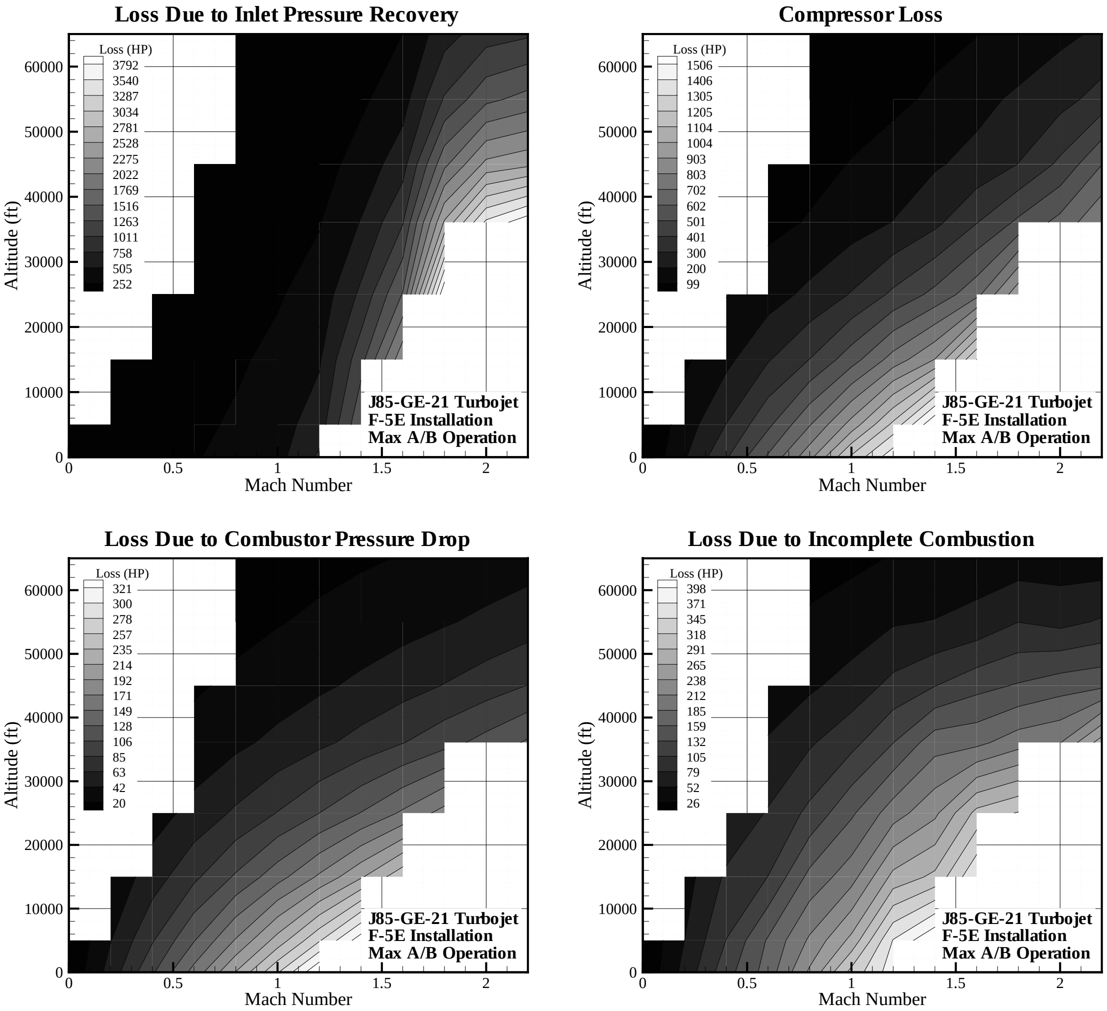
The third and final loss deck created for the F-5E propulsion system is one for loss in thrust work potential. Recall that thrust work potential was defined previously as the potential to do work via isentropic expansion of a gas to atmospheric pressure. Therefore, loss in thrust work potential is a direct measure of loss in ability to produce thrust work, which is, after all, the primary purpose of the propulsion system.

The equations and theory needed to calculate loss in thrust work potential were discussed extensively in Ref. 1. However, there is a simpler way to calculate loss in thrust work potential by repeated runs of the cycle model. The key is to apply the lost thrust work method[6] directly to the results from the cycle analysis code. This method consists of removing losses from the model on a component-by-component basis, and re-running the model between each loss removal. For example, loss in thrust work due to nozzle inefficiency can be calculated by first running the full cycle model with actual component efficiencies. Next, the nozzle thrust coefficient is set to 1.0, and the cycle model is re-run. The thrust work lost due to nozzle inefficiency is simply the difference between the thrust work of the actual model and the revised (no nozzle loss) model. Finally, lost thrust work due to afterburner incomplete combustion can be calculated by setting both the afterburner combustion efficiency and nozzle thrust coefficient to 1.0, re-running the model, and taking the difference between the revised thrust work and that for the previous case. This process is repeated moving from back to front of the engine until the "ideal" (no component loss) propulsion system is obtained. The order in which losses were removed from the J85-GE-21 cycle model is shown in Table 1.

It should be noted that the results obtained from this method depend on the order in which the loss mechanisms are removed from the analysis. The current analysis assumes a change in OPR to hold design point compressor discharge temperature constant when the compressor contribution to lost thrust work is calculated. Also, total fuel flow rate as a function of flight condition is the same throughout the lost thrust

Table 1: Analysis Order for Lost Thrust Method Applied to J85-GE-21 Cycle Model.

Base	***Nominal Performance Model***
Step 1	***Remove Spillage Drag = 0.0 (Fuel Flow Rate Remains the Same as Before)***
Step 2	***Remove Afterbody Drag = 0.0 (Fuel Flow Rate Remains the Same as Before)***
Step 3	***Remove Nozzle Thrust Coefficient = 1.0 (Fuel Flow Rate Remains the Same as Before)***
Step 4	***Remove Afterburner combustion Efficiency = 1.0 (Fuel Flow Rate Remains the Same as Before)***
Step 5	***Remove Tailpipe Pressure Drop = 0.0 (Fuel Flow Rate Remains the Same as Before)***
Step 6	***Remove Turbine Efficiency = 1.0 (Fuel Flow Rate Remains the Same as Before)***
Step 7	***Remove Compressor Bleed for Turbine Cooling = 0.0 (Fuel Flow Rate Remains the Same as Befor)e***
Step 8	***Remove Combustor Combustion Efficiency = 1.0 (Fuel Flow Rate Remains the Same as Before)***
Step 9	***Remove Combustor Pressure Drop – 0.0 (Fuel Flow Rate Remains the Same as Before)***
Step 10	***Remove Shaft Accessories PTO/Bearing Losses = 0.0 (Fuel Flow Rate Remains the Same as Before)***
Step 11	***Remove Compressor Efficiency = 1.0 (T3 SLS, Fuel Flow Rate Remains the Same as Before)***
Step 12	***Remove Inlet Recovery = 1.0 (T3 SLS, F/A Held Same, Fuel Flow Rate Goes Up)***
End	***"Ideal" Performance Model with No Component Loss***


Loss Due to Inlet Pressure Recovery

Compressor Loss

Loss Due to Combustor Pressure Drop

Loss Due to Incomplete Combustion

Fig. 10 Thrust Work Loss Due to Component Inefficiencies (J85-GE-21 in F-5E Installation).

work analysis.

One exception to this last assumption was allowed for estimation of lost thrust work due to pressure recovery. Specifically, engine fuel flow rate is allowed to increase when calculating lost thrust due to pressure recovery in order to capture the effect of pressure recovery on engine physical flow rate. In this regard, thrust work loss due to pressure recovery can be attributed to two factors: impact on cycle pressure ratio and impact on machine physical flow rate. The latter provides increased thrust, but at the cost of increased fuel flow rate. Whereas all other losses are estimated without changing actual fuel and air flow rates, inlet pressure recovery does not adhere to this assumption. Consequently, pressure recovery thrust loss cannot be directly compared to the other thrust work losses, as it is an "apples to oranges" comparison.

None of the four cycle loss mechanisms described previously makes a direct contribution to loss in thrust work potential - they are "hidden" in the engine cycle (including loss due to exhaust residual kinetic energy). This point was discussed in detail in Ref. 11 and it was pointed out that residual kinetic energy is a natural byproduct of the production of jet thrust. It neither contributes nor detracts from the ability to produce thrust work, and is thus transparent as far as thrust work potential is concerned.

Thrust work loss due to component inefficiencies is shown in Fig. 10, and Fig. 11. Several things are noteworthy when these plots are compared to their counterparts for gas horsepower. First, recall that loss in thrust work potential due to bleed/spillage drag and afterbody drag are the same as they were in the gas horsepower and exergy loss decks (as is thrust work). They are therefore omitted from Fig. 10 in the interest of brevity.

A second item of note is the way that the contours change shape between the gas horsepower loss deck and the thrust work potential loss deck. As a rule, the contours are "steeper" for thrust work potential than

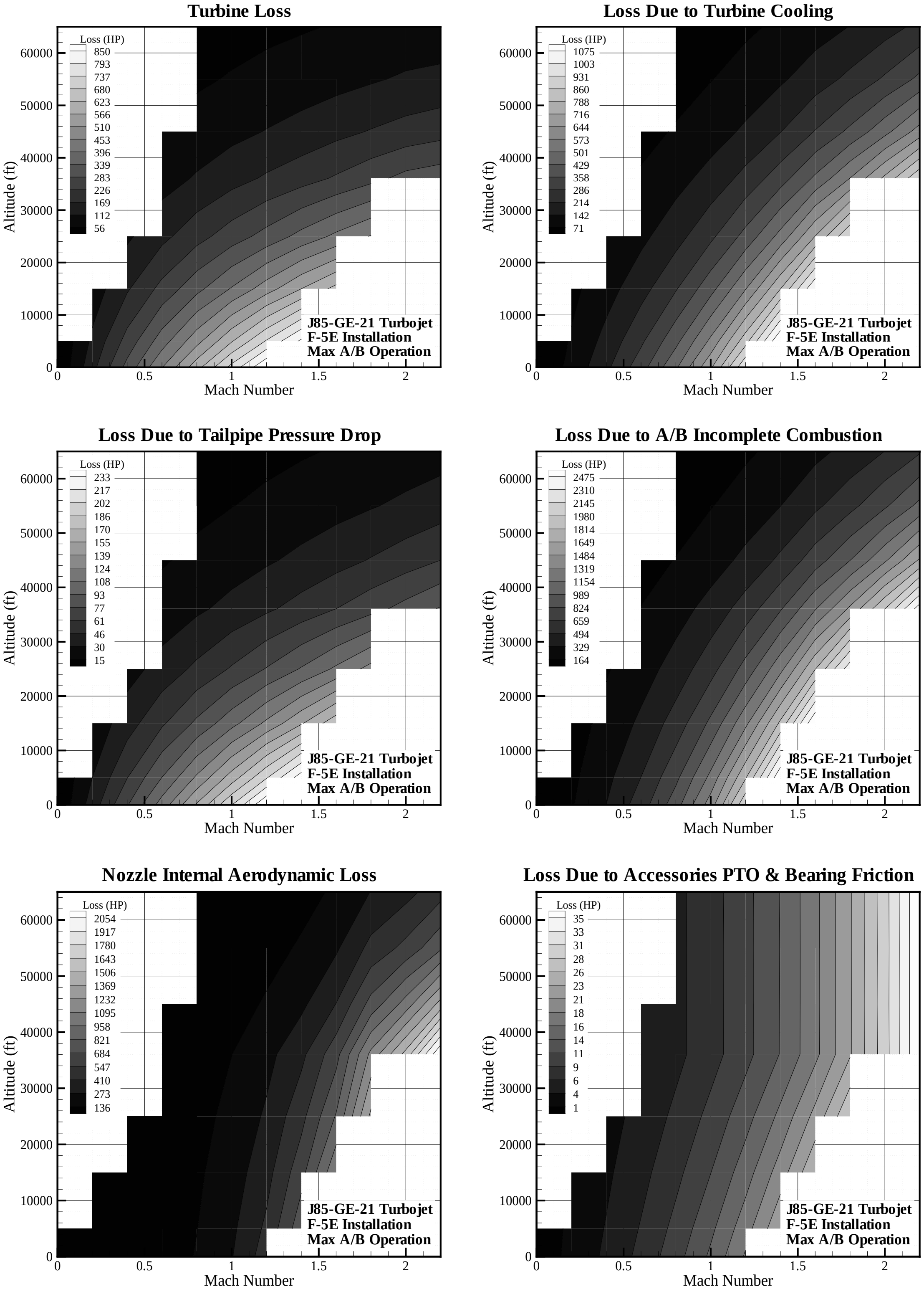


Fig. 11 Thrust Work Loss Due to Component Inefficiencies (J85-GE-21 in F-5E Inst'ln, ctd).

they are for gas horsepower. In other words, the loss contours for thrust work potential are more strongly driven by flight Mach number than they are for gas horsepower. The reason for this is that thrust work potential can be expressed as the product of stream thrust and flight velocity. Therefore, vehicle velocity (and Mach number) is a strong driver on loss in thrust work potential. A natural repercussion is that during static operation, the loss in thrust work potential goes to zero. Consequently, there is no loss in thrust work potential in any component during static operation. This may seem counterintuitive at first, but it makes sense if one realizes that *an engine cannot generate thrust work during static operation*. *Therefore its total thrust work potential at this condition is zero and loss thereof is also zero.*

Comparison of Loss Decks

The primary difference between the three loss decks is the way each bookkeeps loss. Since exergy is a measure of absolute work potential, it includes all sources of work. One would therefore expect that the exergy in the fuel is much higher than gas horsepower and thrust work potential of the fuel, and this is reflected in the loss decks developed in this paper. Moreover, one would expect that the total exergy losses are far higher than total gas horsepower losses or total thrust work potential losses, and this is exactly what the loss decks show.

An interesting difference between the three loss figures of merit can be observed in loss due to accessories PTO & bearing friction. Note that the plots for PTO/bearing losses are identical as measured by exergy and gas horsepower figures of merit. This is because PTO/bearing loss represents a decrease in physical shaft work. Physical shaft work can be thought of as energy with zero entropy, which means that all of the energy is available to do useful work. Therefore, both exergy and gas horsepower yield identical results: a loss of 1 HP results in a reduction of 1 HP exergy or gas horsepower.

This is not the case for thrust work potential. Observation of loss in thrust work due to PTO/bearing losses shows that the reduction in thrust work is less than the loss in shaft work. The difference appears as residual kinetic energy in the exhaust. This is energy that makes no contribution to useful thrust work on the aircraft, and so does not appear as a loss.

Conclusions

The methods described in this paper are a critical piece needed for construction of truly practical loss management models for use in propulsion system analysis and design. The F-5E example selected for analysis was intentionally chosen to be simple enough to facilitate understanding while still being representative of the complexity typically found in modern propulsion systems. These results show conclusively that it is possible to build a detailed loss deck representing propulsion system performance. Moreover, this loss deck can be constructed such that it bookkeeps all losses and work production in a *comprehensive* and *consistent* fashion, a necessary prerequisite for construction of practical loss management models for the aircraft as a whole.

The results from this analysis are useful as a guide to show where the most significant losses are occurring in the propulsion system. In particular, the “loss envelope” concept used to depict the three loss decks for the F-5E is a very simple and intuitive means of displaying voluminous quantities of thermodynamic performance data. It is very easy to see trends in loss data, determine which flight conditions have the greatest loss, or determine the relative magnitudes of losses for a given flight condition. In addition, errors in the analysis process are usually very evident in the loss envelope plots, thus facilitating simple visual checks on analysis calculations.

Acknowledgements

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