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Method for Propulsion Technology Impact Evaluation via Thermodynamic Work Potential

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Recent developments in thermodynamic work potential methods based on the second law of thermodynamics are enabling new and innovative approaches to systems design. These methods can assist designers in quantifying the impact of new technology in a comprehensive and consistent manner. Work potential methods allow the creation of a truly unified picture of aerothermodynamic and weight benefits associated with a given technology and, furthermore, allow the explicit calculation each individual contributing factor constituting that impact. The basic theory for technology evaluation via work potential, how it can be directly related to vehicle mass properties (fuel weight), and a demonstration of its application on a classic propulsion technology selection problem applied to the Northrop F-5E aircraft are described.

Introduction

TYPICAL design practice used for propulsion system technology studies today is to measure technology impact through parametric studies using modeling and simulation. The starting point is an existing baseline design from which parametric variations on technology assumptions are examined.[1] This is usually accomplished by incorporating a new technology concept into the propulsion system performance model and creating a new engine performance deck. This deck is then "flown" in a vehicle model (such as a mission analysis model) to estimate vehicle weight, performance, etc., of the revised design. The resized vehicle weight and performance can then be compared to that of the baseline vehicle, the delta between the two being the net impact of that technology. This approach can be very accurate and effective and has been a standard method for evaluation of technology impact for many years.

However, this approach has some limitations. First, it gives no information regarding how the individual technology benefits at the subsystem level combine to make up the net benefit at the system level. It is frequently of interest to know what these individual benefits are, as well as the magnitude of their contribution. Consequently, the standard technology modeling and simulation approach at times needs to be augmented with a means of providing information regarding the underlying mechanisms driving the net technology benefit (or penalty). Second, simple technology evaluation at the system level has another limitation in that when multiple technologies are to be examined, the aggregate impact of these technologies can be evaluated at the system level, but it is frequently difficult to discern the individual contribution of any single technology. This is due to interactions between technologies, wherein one technology may have a "proverse" or adverse impact on other technologies and, thus, change their cumulative net effect.

Some guidance as to how one may best overcome these shortcomings can be gained by considering vehicle design at its most fundamental level. All vehicles must obey the same laws of physics and are subject to the same fundamental limitations. Given this situation, there must be a common thread of analysis applicable to all classes of vehicle. Specifically, if all vehicles must obey the same laws of physics, then there must be a common figure of merit applicable to any vehicle, and it should be possible to formulate a generalized theory of vehicle design based on these fundamental principles.

Generally, the fundamental principles governing vehicle deign are Newton's laws of motion and the laws of thermodynamics. In fact, Newton's second law of motion and the first law of thermodynamics are the cornerstones on which virtually all vehicle analysis methods are built today, with the other laws playing a supporting role. However, there is something to be gained by truly applying the "second tier" laws to their fullest extent. In particular, the second law of thermodynamics has never been central to the vehicle design process, but holds considerable promise as a fundamental principle to guide vehicle designers.

The reason that the second law is a promising tool for vehicle designers is that it suggests the concept of thermodynamic work potential. To understand this, consider that all vehicles must consume work potential (usually in the form of fuel) to function. At the most fundamental level, it is the usage and loss of thermodynamic work potential that drives virtually every aspect of a vehicle's design and performance. One would, therefore, expect that the tracking and optimization of work potential usage would be a central activity in the vehicle design and technology selection process. Yet, modern vehicle design methods make little or no use of the second law of thermodynamics and the work potential concept it suggests.

In short, there simply is no rational and organized method in place today to enable the estimation and tracking of work potential usage in vehicle design, even though work potential is the lifeblood of vehicular motion. Application of work potential concepts to vehicle design is the key to enabling calculation of usage and loss in work potential incurred in each thermodynamic process relevant to a vehicle's operation. This gives a designer the ability to identify and target the most significant sources of loss for improvement via the infusion of new technologies and concepts. Furthermore, the application of these loss management methods[2] provides a means of estimating the individual impact of disparate technologies in terms of a common figure of merit (FOM).

The approach used herein applies traditional parametric perturbation methods in conjunction with loss management methods. It has been shown that these two methods deliver information that is complimentary,[3] and so their use in combination with one another should logically lead to useful results. Their application in propulsion technology trade studies capitalizes on the strengths of both and negates their individual weaknesses.

The potential applications of loss management methods for technology evaluation are explored through illustration by example. The example used herein is based on an aircraft that is a known quantity,

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the Northrop F-5E powered by J85-GE-21 engines. This paper defines a parametric family of engine cycle/technology concepts based on the J85-GE-21 and applies the loss management methods to the analysis and quantification of technology impact for the F-5E/J85 engine/airframe combinations. The result is a more detailed description of cycle technology impact than can be obtained using standard cycle and mission analysis methods.

Thermodynamic Work Potential in Vehicle Design

The idea of work potential is a concept that all people naturally intuit. For instance, it has been understood for centuries that a rock at the top of a hill has more work potential stored in it than does one at the bottom. Humankind has learned to utilize the work potential stored in the environment to power sailing ships, drive windmills, transport goods, conduct commerce, etc. Yet, although it is an easily intuited concept, a formal definition of work potential eluded scientific inquiry for centuries. It is only recently that the general concept of thermodynamic work potential has become a precisely (scientifically) defined quantity.

In the broadest sense, that which we think of as work potential is thermodynamically related to equilibrium (in a physical, chemical, thermal, or any other sense). Specifically, the farther a given substance is out of equilibrium with its environment, the greater its potential to do useful work.[4] In effect, the higher a rock is on the hill, the more work can be extracted in taking it to the bottom of the hill. It is the constant state of nonequilibrium that drives the world around us. Today, this concept is embodied in the second law of thermodynamics, and the analytical techniques developed to quantify work potential are referred to as second-law methods.

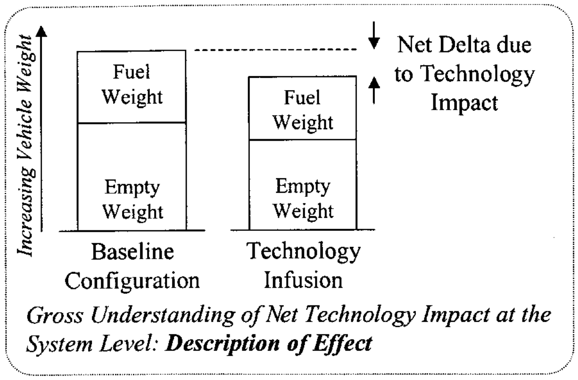
These second-law methods can be used to calculate the maximum work that can theoretically be extracted from any substance in a given environment. Just as there is a well-defined upper limit on the amount of work that can be extracted from moving a rock down a hill, there is also an upper limit on the maximum work that can be obtained from fuel. This maximum work is commonly known in the thermodynamics community as exergy.[5]

During the course of an aircraft's mission, the exergy initially stored in the mission fuel is entirely consumed. A portion is destroyed due to propulsion system losses. The remainder appears as thrust work, a portion of which is in turn used to overcome drag (another loss), or power the vehicle's systems (further losses). The remainder is stored as potential and kinetic energy of the airframe. The loss management method alluded to earlier is nothing more than a formalized means of quantifying and tracking this usage of work potential throughout the vehicle mission.[6]

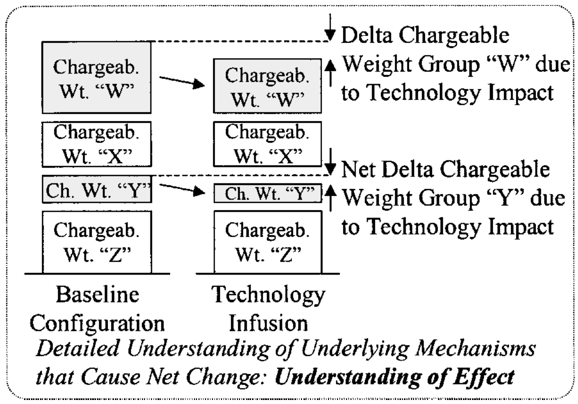
The central concept allowing the presentation of a unified FOM for both aerothermodynamic and weight impact of new technologies is the notion of chargeable gross weight. To understand this, consider the earlier statement that fuel has a known quantity of work potential stored within. Therefore, there must be a relationship between usage of work potential and fuel weight. For instance, if the compressor in the engine has some losses associated with its operation, then there must also be a quantity of fuel that was consumed to offset those losses. This is the fuel weight chargeable to compressor losses. If this fuel weight is added to the empty weight of the compressor, the result is effectively the component of vehicle gross weight chargeable to the compressor and its aerothermodynamic performance. Likewise, any other aerothermodynamic loss can be quantified in terms of chargeable fuel weight and, ultimately, chargeable gross weight. It is this concept of chargeable gross weight that serves as a unifying FOM that enables direct comparison of mass properties and thermodynamic performance aspects of new technology concepts.

Technology Evaluation via Loss Management Models

To understand the usefulness of loss management methods for evaluation of technology impact, consider what value would be added by their application to this problem. The primary strength of vehicle loss management models is their ability to discern each individual contributor to performance. Therefore, loss management models can be used to identify the "heavy hitters" that dominate vehicle weight and thermodynamic performance. This type of knowledge is potentially very useful for tailoring technology cost/benefit studies toward identifying those technologies that best target the major contributors to vehicle weight and loss.



a)



b)

Fig. 1 Differences between technology impact as estimated using gross weight and chargeable gross weight.

This idea is illustrated in Fig. 1, which compares two hypothetical scenarios. The scenario in Fig. 1a represents the analysis of technology impact using standard mission analysis to determine empty weight and gross weight required to complete a specified mission for the baseline vehicle. Subsequently, an advanced technology vehicle is analyzed for the same mission to arrive at a revised estimate for required empty and fuel weight to complete the mission. The difference between the two cases is taken to be the net effect of adding new technologies to the baseline design.

The scenario in Fig. 1b represents the evaluation of that same technology in terms of chargeable gross weight groups. In this case, the baseline design gross weight is partitioned into chargeable components using the unified weight/performance approach.[2] Next, the same analysis is conducted on the advanced technology design. The differences between the chargeable gross weight groups constitute the technology impact. Therefore, in this hypothetical example, the proposed technology had an impact on chargeable gross weight groups W and Y (shaded), but had no significant impact on any of the other chargeable weight groups. The result is an understanding of the underlying effect that the technology has on each functional component as opposed to a description of the net effect at the system level.

The counterpoint to this approach is that not all technology concepts manifest themselves as a change in weight or thermodynamic performance. Instead, a technology may receive consideration due to its impact on some other aspect of vehicle capability. Therefore, the methods proposed in this paper have an implied limitation on the generality of the statement. Specifically, they are only valid for those technologies that have a significant impact on vehicle mass and/or thermodynamic performance. For the more general problem where a variety of disparate attributes must be considered (such as noise, emissions, etc.), it is necessary to apply a multiattribute decision-making method such as joint probabilistic decision-making techniques.[7]

Application to the Northrop F-5E

As mentioned earlier, the focus of this paper is on engine technology and its evaluation. Obviously, there are an almost infinite variety of technology combinations that would be of interest to examine, particularly with regard to component-specific technologies. It is clearly impossible to examine all of these and, in any event, most would be of fleeting interest. Therefore, rather than examine the impact of a set of specific component technology scenarios, the focus here is on examination of more general technologies that are truly fundamental to the state-of-the-art in the gas-turbine propulsion industry: overall (cycle) pressure ratio (OPR) and turbine inlet temperature (TIT). These two parameters are good indices of technological capability for all gas-turbine prime movers and will be of lasting interest well into the future.

Moreover, selection of OPR and turbine inlet temperature is a classic cycle trade for turbojet engines. These parameters are well known and have historically been selected to achieve the highest possible performance commensurate with current technology capability and vehicle-specific objectives. The result has been a long-term trend toward increased OPR and TIT capability, and examination of a typical exergy analysis of a turbojet engine quickly reveals one of the reasons why: Increasing OPR and TIT decreases losses due to exhaust residual heat and combustion irreversibility, respectively. These are the two largest contributors to exergy loss in the propulsion system (and, in fact, the entire airframe). Therefore, one has a large incentive to develop technologies that allow increased OPR and TIT capability.

The factors limiting increases in OPR and TIT are usually materials and heat transfer technology. Consequently, the final selection of OPR and TIT is usually a compromise between high performance obtainable with the high OPR/TIT enabled by state-of-the-art technology on one hand and the desire to have a mature, reliable, low-maintenance propulsion system on the other.

F-5E Mission Analysis Model and J85 Cycle Model Description

By way of background, it is useful to describe the basic analysis setup used in this study so that the reader may have a better idea of the assumptions inherent to the results presented later. First, the J85 engine performance data used in this paper were generated using a standard NEPP/INSTAL cycle and installation model described in Ref. 2. This model was developed based on manufacturer's performance data and is used to obtain an engine performance deck for mission analysis. It is also used to obtain temperature, pressure, and flow rate at every engine station to calculate work potential (and loss thereof) in the propulsion system. The result is effectively an engine "loss deck" describing propulsion system loss as a function of flight condition. Drag polars for this analysis are taken from manufacturer's flight-test data and were also used to create an aerodynamic loss deck describing drag work as a function of flight condition and vehicle weight.

The F-5E mission used in this paper is a 225-n mile radius subsonic area intercept and was developed based on manufacturer's data using standard mission rules and allowances. The F-5E mission analysis model used in this paper is implemented in the flight optimization system (FLOPS) mission analysis code and is described extensively in Ref. 2. This was then used to create a mission time history, as well as sized vehicle weight and performance. Finally, the mission time history is used in conjunction with the propulsion and aero loss decks to create a time history of the F-5E exergy usage at every instant throughout the design mission. This exergy usage is then integrated through the elapsed mission time to obtain total exergy chargeable to each loss mechanism (engine component losses, aerodynamic drag, etc.).

Classical TIT/OPR Technology Trade Study Results

To illustrate the application of loss management methods to OPR/TIT selection, this discussion will start with an overview of

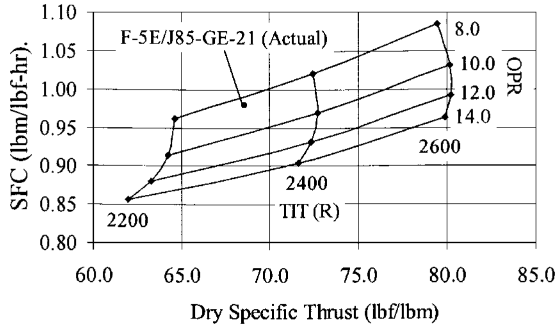


Fig. 2 Parametric variation of specific thrust and SFC for J85 derivative cycles over a range of OPR and TIT (full military power).

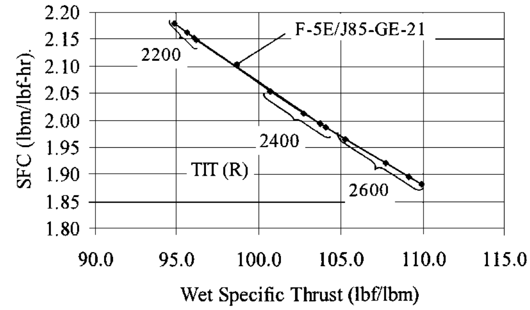


Fig. 3 Parametric variation of specific thrust and SFC for J85 derivative cycles over a range of OPR and TIT (maximum A/B).

the classic analysis methods commonly used in cycle technology trade studies today. The first step in this process is to select a range of OPR and TIT for study. Generally, this range is chosen to encompass the existing cycle, which is an OPR of 8.6 and a TIT of 2300°R for the J85-GE-21. For the purposes of this study, OPR was varied from 8.0 to 14.0, and TIT was varied from 2200 to 2600°R. The design point efficiencies and cooling flow rates for the basic J85 cycle model remained unchanged for all cases investigated. Therefore, increases in TIT and OPR imply improved heat transfer and materials technology, particularly in the turbine.

Typical results of full-power, nonafterburning operation for an OPR/TIT trade study are shown in Fig. 2 for 12 derivatives on the J85 cycle (four levels of OPR and three levels of TIT). The results of this analysis show that turbine inlet temperature is a strong driver on specific thrust and specific fuel consumption (SFC), with higher turbine inlet temperatures causing increased specific thrust and SFC. The increase in specific thrust is due to increased tailpipe temperature and pressure caused by elevated TIT. Figure 2 also shows that increases in OPR cause a strong reduction in SFC, as well as a weak change in specific thrust. The reduction in SFC arises due to decreased exhaust heat losses because the cycle approaches the Carnot ideal as compressor discharge temperature approaches the turbine inlet temperature. The change in specific thrust is due to changes in tailpipe pressure and temperature precipitated by variation of turbine power extraction required to drive the compressor.

Similar to Fig. 2 for full power, afterburning (A/B) operation is shown in Fig. 3 for the same family of 12 J85 derivatives. Note that TIT is the dominant influence on both SFC and specific thrust, with OPR exerting a moderate influence. Increasing TIT leads to increased A/B specific thrust and decreased A/B SFC, whereas increasing OPR also leads to increased specific thrust and decreased SFC. Also note that the matrix of engine cycles collapse to a single line. This is because the fuel-to-air ratio in the tailpipe is near stoichiometric. Therefore, total fuel flow rate is dependent only on airflow rate and is independent of TIT or OPR. Airflow rate is, in turn, dependent on the engine sizing criterion, which, in this case, is 3500 lb uninstalled thrust during dry, sea level static (SLS) operation.

The trends shown in Fig. 3 are typical and are just as would be expected from standard cycle analysis. However, note that this analysis reveals nothing about how close these engines are to the ideal. Furthermore, it does not reveal anything about the source or magnitude of losses in the propulsion system.

The next step in the evaluation process is to "fly" each of the 12 installed engines in the mission analysis model to estimate the impact of cycle technology on overall vehicle performance. The mission analysis model used for this purpose is the same F-5E mission model described earlier. It is assumed that engine dry thrust, wing size, and zero fuel weight are held constant in this parametric study, whereas mission fuel is allowed to vary to complete the mission.

These assumptions are somewhat restrictive in that secondary effects of engine cycle changes are not captured in the vehicle sizing process. In effect, aircraft nonfixed weight groups are not allowed to scale with gross weight, and maneuver performance is allowed to vary as gross weight fluctuates. Moreover, nacelle size (drag) and engine weight do not change with engine cycle. Although these effects are important, they are not included here because they would distract from the pedagogical value of this example. In any event, incorporation of more sophisticated assumptions and scaling laws is relatively straightforward.

Carpet plots for sized vehicle takeoff gross weight are shown in Figs. 4 and 5 for each of the 12 derivative cycles investigated. Not surprisingly, increasing TIT and OPR tend to reduce vehicle gross weight and mission fuel weight via reduction in fuel burn required to complete the mission. Note that the assumed range of cycle parameters yields mission fuel weights ranging from 4500 to 3850 lb, or from +2 to −13% of baseline mission fuel. However, although this analysis reveals how cycle technologies changed net vehicle weight, it reveals very little about how the cycle technologies affected that change in weight. Moreover, if the vehicle empty weight groups had been allowed to scale with gross weight, the fundamental mechanisms would be further obscured.

Finally, although these results show that there is a strong incentive to improve maximum allowable OPR/TIT capability, these improvements do not come without cost. In this case, decreased takeoff gross weight comes at the expense of decreased performance, as illustrated in the carpet plots of Figs. 6–8. Figures 6–8 show specific excess power at combat, climb ceiling, and top speed, respectively, for the F-5E with the family of J85 derivative cycles. Note that, in all cases,

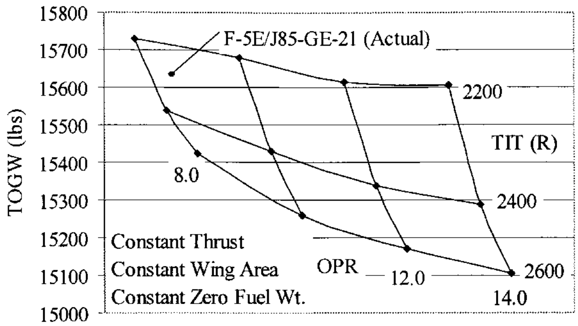


Fig. 4 Carpet plot for sized takeoff gross weight as a function of OPR and TIT for the F-5E with J85 derivative engines.

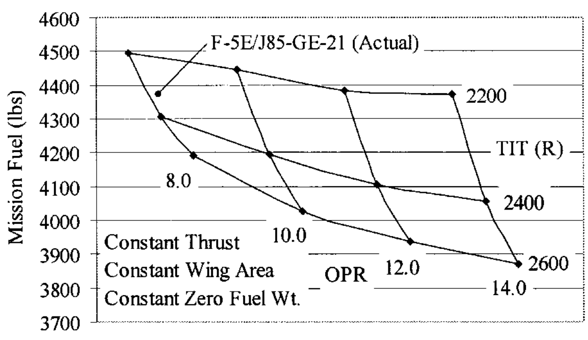


Fig. 5 Carpet plot for sized mission fuel weight as a function of OPR and TIT for the F-5E with J85 derivative engines.

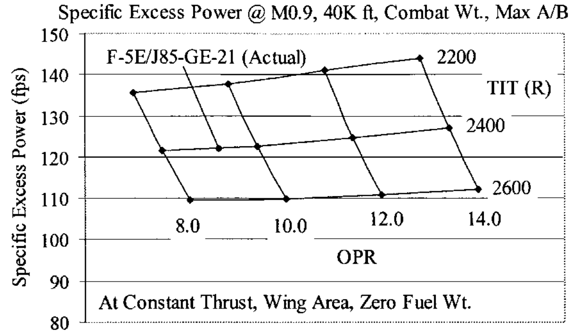


Fig. 6 Carpet plot of F-5E specific excess power for a range of OPR and TIT.

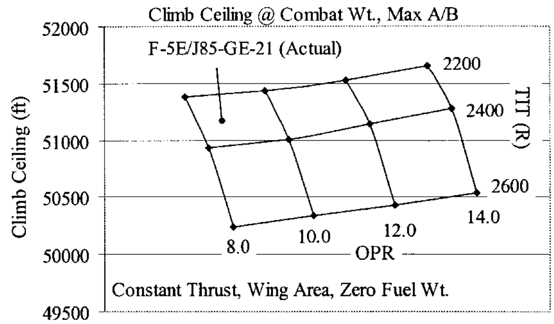


Fig. 7 Carpet plot of F-5E climb ceiling for a range of OPR and TIT.

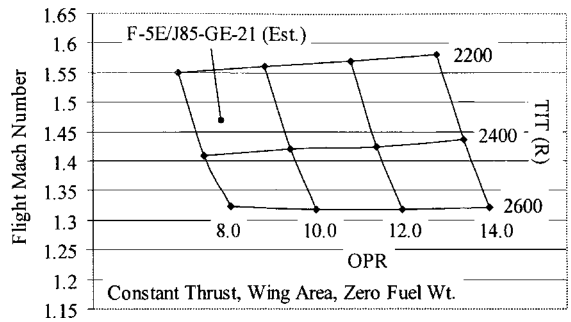


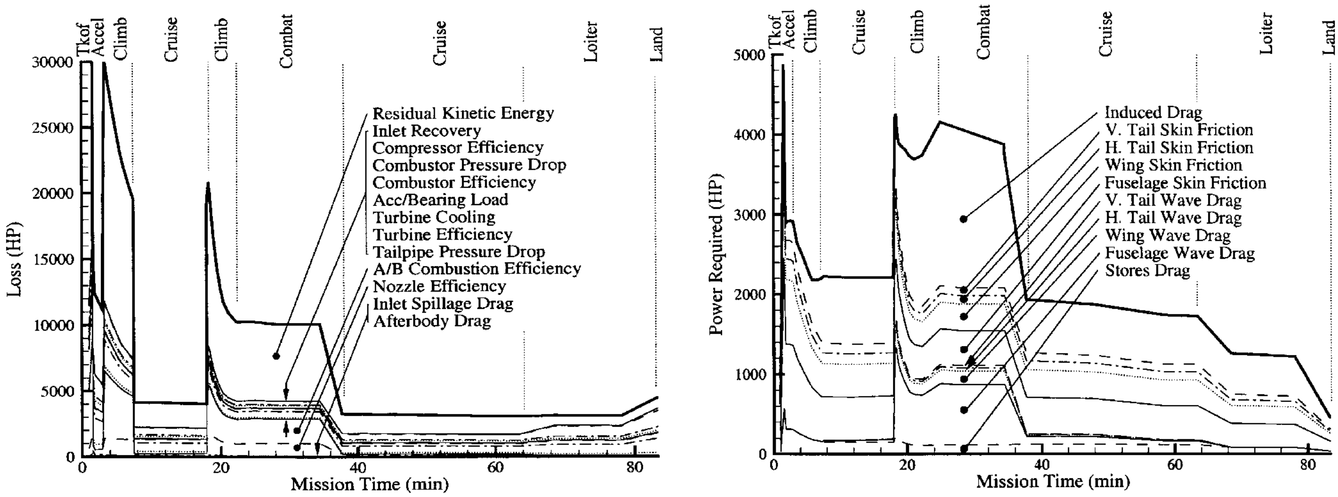
Fig. 8 Carpet plot of F-5E top speed for a range of OPR and TIT.

OPR has only a weak influence on performance, whereas TIT exerts a dominant influence. Figures 6–8 show that increased TIT tends to decrease combat maneuver performance. The reason for this is that as TIT is increased, the maximum temperature rise across the A/B decreases (because there is less oxygen available in the tailpipe), and so the thrust augmentation provided by the A/B is considerably decreased. As thrust augmentation decreases, combat performance is degraded. This is a classic cycle trade that must be established for all fighter aircraft, regardless of mission or manufacturer.

The results of this analysis yield a very clear picture of how changes in TIT and OPR impact the sized vehicle mission fuel and maneuver performance. However, this is the limiting extent of detail available using standard analysis methods. What is not shown is how OPR and TIT technology capability impacts each individual source of loss that contributes to the larger whole. To put it differently, there is no means by which the individual contributors to mission fuel usage can be estimated. Enter loss management methods.

Cycle Technology Impact on F-5E Chargeable Weight

The primary strength of loss management methods is their ability to provide increased insight as to which are the primary factors driving the design, estimate individual contributors to fuel usage, and track their interactions with each other. Because the objective here is to observe the impact of OPR and TIT on fuel chargeability, a loss management formulation is used in conjunction with exergy



a) Propulsion system exergy loss **b) Aerodynamic drag work**

Fig. 9 Exergy usage as a function of mission time for the F-5E subsonic area intercept mission.

analysis. The result is an estimate on chargeable fuel weight for the matrix of cycle candidates. This involved the creation of exergy loss decks for the 12 engines studied in this paper, each of which was subsequently evaluated in the loss management model. In all cases, the aerodynamic performance was unchanged, and the mission analysis was subject to the same assumptions as before. The only change in the cycle analysis was the design point TIT and OPR, all other parameters remaining the same.

The result from this analysis is a time history of work potential usage throughout the F-5E design mission, as shown in Fig. 9 for the baseline F-5E configuration. Figure 9a shows how the propulsion system uses the exergy stored in the fuel during each mission leg. All loss mechanisms are shown "layered" one on top of another, and the loss mechanism associated with each layer is annotated in Fig. 9a. Note that the climb and combat segments are characterized by high losses and high power output, whereas the cruise legs are characterized by a relatively low power output and fewer losses. Figure 9b shows a drag work time history for each mission leg. Not surprisingly, the combat leg exhibits the highest drag power required, with cruise power required being relatively low.

The total work potential lost is proportional to the area of each layer shown in Fig. 9. Comparison of these areas clearly shows that combustion irreversibility and exhaust heat are far and away the greatest sources of loss in exergetic work potential experienced in the F-5E. Not surprisingly, exhaust heat losses and combustion irreversibility are strongly driven by the selection of OPR and TIT, thus the gas-turbine industry's continued emphasis on technologies that enable improvements in these parameters.

The integrated work potential usage results from all 12 cycle candidates are summarized in Fig. 10, which shows the variation of exergy usage as a function of OPR for three levels of TIT ranging from 2200 to 2600°R. If the losses shown in the loss time history of Fig. 9 were integrated to produce a total loss stackup, that stackup would appear in Fig. 10 as an infinitesimally thin vertical strip at TIT = 2300°R and OPR = 8.8.

Close inspection of Fig. 10 clearly shows that increases in OPR tend to reduce exergy loss, primarily through reductions in exhaust residual heat and combustion irreversibility. Furthermore, note that increasing TIT tends to reduce total exergy loss, especially between 2200 and 2400°R. This is due to a marked decrease in A/B combustion irreversibility (because there is less oxygen in the tailpipe as TIT increases) and also because there is an accompanying decrease in exergy loss due to exhaust heat. This latter trend is counterintuitive based on simple Brayton cycle analysis, but arises because elevated TIT enables the use of a smaller propulsion system, resulting in a net decrease in loss at the vehicle system level.

Although component losses play a small role in total F-5E exergy loss, they are not insignificant. As one would expect, component losses generally increase with increasing OPR (due to increased turbomachinery losses), but decrease with increasing TIT (due to reductions in propulsion system size). Also, induced drag work is markedly increased with increasing TIT. Finally, note that approximately 60% of total exergetic losses in the F-5E design mission occur due to exhaust heat, combustor irreversibilities, and A/B irreversibilities. These data suggest that there is far more to be gained by concentrating on technologies to enable reductions in these three sources of loss than in all others combined.

These same data can be expressed in the form of chargeable mission fuel, as shown in auxiliary axis of Fig. 10. This axis shows loss expressed in terms of mission fuel rather than thermodynamic work potential. Placed in this light, the results of the work potential analysis presented herein are rather startling: The results indicate that roughly 90% of total mission fuel consumed is used to offset losses in the F-5E propulsion system. Admittedly, the F-5E is vintage technology by today's standards, but the propulsion system remains the dominant source of loss even in today's most advanced gas-turbine engines.

Of the 4000 + lb of mission fuel used in the F-5E, nearly 1500 lb is needed just to offset exhaust heat losses. A further 1000 lb is needed for combustion irreversibility, along with 500 lb for afterburner irreversibility and 500 lb for exhaust residual kinetic energy losses. In the end, a paltry 500 lb of fuel is actually converted into thrust work to offset drag losses. Clearly, there is much to be gained at the vehicle level by continued pursuit of advanced propulsive technologies that will enable reductions in propulsion system losses.

The creation of Fig. 10 is effectively the link between propulsive technology aerothermodynamic benefit and mass properties benefits. If a detailed model for engine weight as a function of TIT and OPR were incorporated into this analysis, it would be possible to track in great detail exactly how TIT and OPR drive changes in vehicle gross weight. The result, as mentioned earlier, is information yielding an understanding of the underlying effect behind the technology benefit. Moreover, this information is a powerful guide to show where there is room for improvement in the future.

Finally, the information contained in Fig. 10 can also be used as a means of cost accounting in vehicle economic analysis. For instance, because it is possible to calculate the fuel weight associated with component losses analytically, it is also possible to estimate mission fuel cost chargeable to component losses (or drag losses, cycle losses, etc.). This is information that can not be obtained through conventional vehicle analysis techniques.

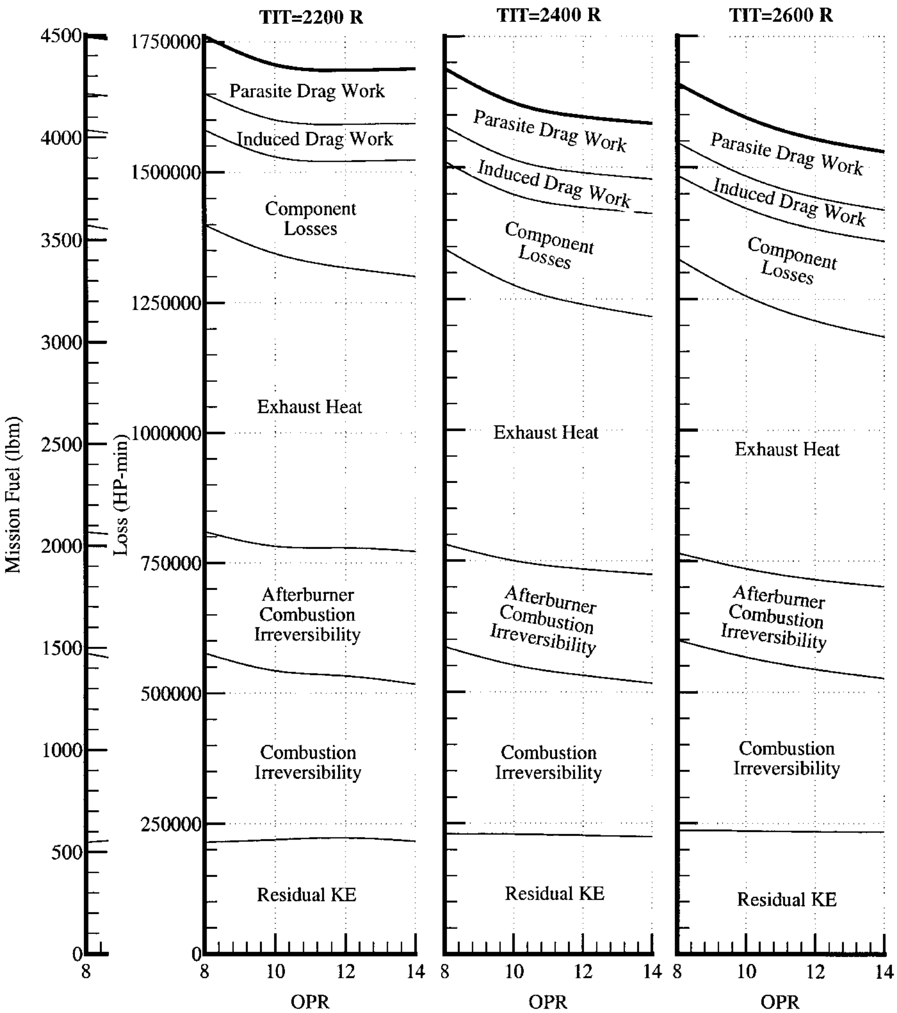


Fig. 10 Exergy and chargeable fuel weight usage for F-5E subsonic area intercept mission as a function of engine cycle pressure ratio and turbine inlet temperature.

Conclusions

The results of this paper clearly show that the application of loss management methods provide information above and beyond that available using typical parametric analysis methods. Specifically, loss management methods provide results that convey a clear understanding of exactly how each loss mechanism is impacted by changes in technologies or cycle parameters. All of these changes are quantifiable in terms of thermodynamic loss, which can be directly translated into chargeable fuel weight.

A second objective of this paper has been to illustrate how the loss management methods can be applied to ordinary cycle studies to obtain useful information. Based on the analysis shown for the simple J85 cycle trades, it is clear that the vast majority of mission fuel consumption is due to cycle effects. In fact, as measured relative to the exergy FOM, most of the mission fuel burn is due to the cycle itself, which is, in turn, limited by available technology. The remaining loss is due to two mechanisms: inefficiencies in the engine components themselves and aerodynamic drag work done by the vehicle on the atmosphere. These last two losses each account for roughly 10% of the total exergy usage for the F-5E.

The upshot of this analysis is recognition that there is much more to be gained by continued improvements in basic cycle technology and capability than there is in individual component technologies. This is not to say that component technology improvements are unneeded. Quite the contrary, component technologies are ultimately the means by which improved cycles can become a practical reality.

Finally, note that although the J85 example used in this study is vintage technology by current standards, the same situation still applies to today's engines: The vast majority of losses in work potential are attributable to cycle effects. Therefore, the results of this analysis are at least as applicable for modern machines as for the J85. In fact, one could argue that this is even more applicable for modern machines because the relative maturity of current jet engine technology implies that is more difficult to obtain significant performance increases and, therefore, more important to identify and focus on those areas offering high-performance payoffs.

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