A Work Availability Perspective of Turbofan Engine Performance

AIAA2001-0391

Presented at

39th AIAA Aerospace Sciences Meeting and Exhibit

Reno, NV

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January 9, 2001

Motivation

- From a thermodynamic standpoint, *an aircraft in cruising flight produces nothing but loss*
- The crux of the aircraft cruise optimization problem is optimal partitioning of these losses
- The first law of thermodynamics is misleading in this regard because it can only measure the *quantity* of energy, not the *quality* (work-producing potential)
- Second law methods provide powerful insight as to the true thermodynamic cost of each loss source
- Work potential methods put all losses on an equal (directly comparable) footing

Introduction

- There is a growing need to accurately calculate loss of propulsive work potential relative to a thermodynamic ideal
- This has led to interest in applying second-law methods to measure loss in aircraft propulsion systems
- Conventional cycle analysis → flow of *energy*; second law-based method → flow of *work potential*
- The purpose of this paper is to present a work availability perspective of the how engine cycle impacts thermodynamic performance of gas turbine engines:
  - Background - definition of exergy
  - Classical presentation of cycle impact
  - Second law description of cycle impact
  - J85-GE-21/F--5E case study

Step 0: Define Loss

- The definition of loss depends to some extent on the system under consideration as well as the objectives of the analyst
- There is more than one valid metric of work potential available:
  - Exergy
  - Available energy (gas horsepower)
  - Thrust work potential
  - etc.
- Loss can also be defined in ways other than reduction in ability to do work:
  - Vehicle chargeable weight
  - Economic cost

Comparison of 1st and 2nd Law Analysis

First law

- Physical principle: Energy is conserved -

$$gz_1 + \frac{V_1^2}{2} + u_1 + \frac{P_1}{\rho_1} + Q = gz_1 + \frac{V_1^2}{2} + u_2 + \frac{P_2}{\rho_2} + W$$

Second law

- Physical principle: Entropy of the universe cannot decrease

$$\sum Ex_1 = \sum Ex_1 + Ex_{loss}$$

- Not all components of exergy are available to do work in a gas turbine engine:
  - Thermal energy in exhaust
  - Irreversible mixing of hot + cold streams
  - Irreversible mixing due to difference in exhaust stream and ambient species concentrations
- Must bookkeep these components of availability appropriately in order to properly use it for engine analysis

Definition of Exergy

"The Carnot Reference FoM"

Exergy (or Availability): A thermodynamic property describing the maximum theoretical (Carnot) work that can be extracted from a substance in taking it from a prescribed state (Temp., Press., & Composition) to *chemical*, *mechanical*, and *thermal* equilibrium with the environment:

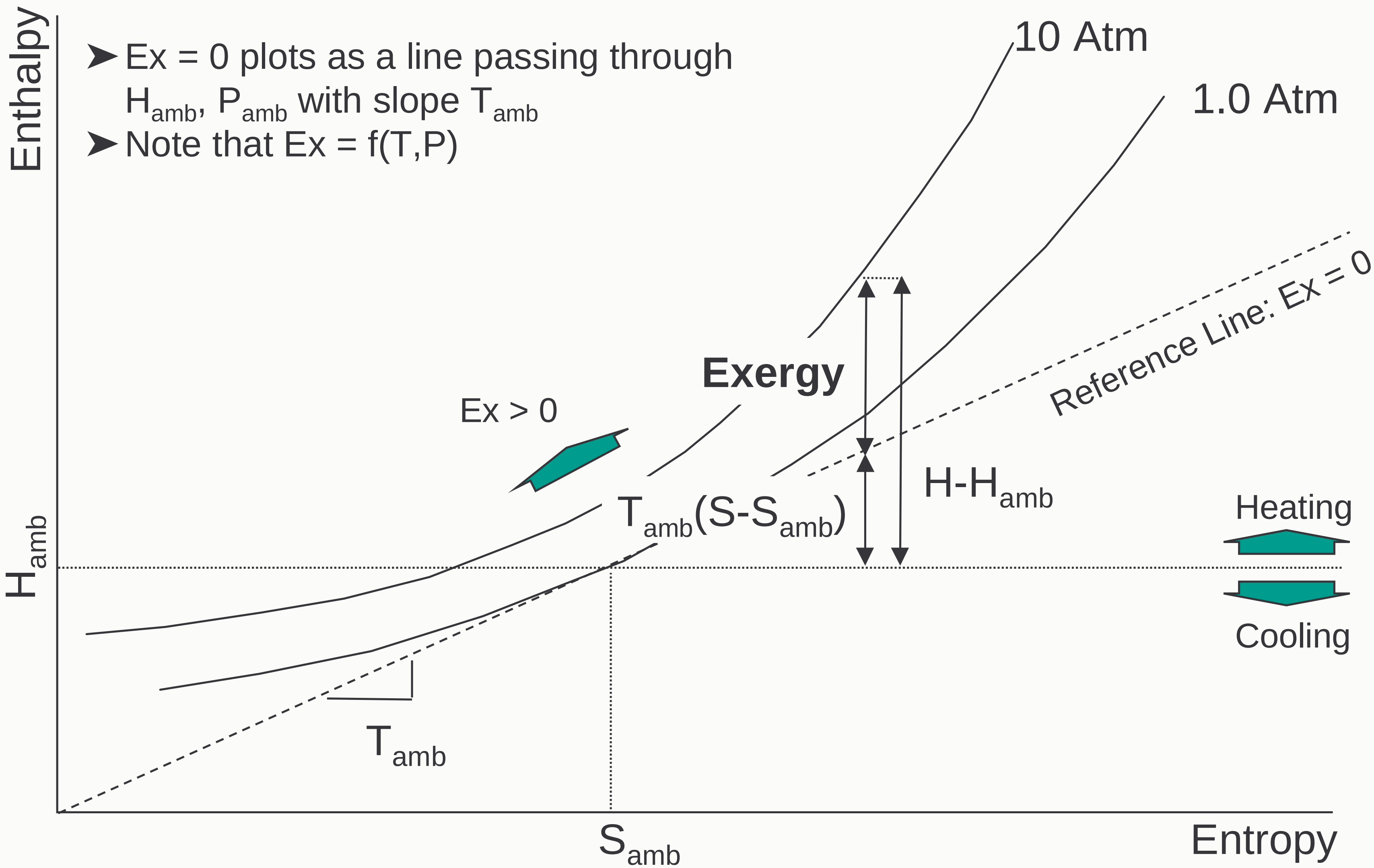
$$\mathbf{Ex = (H - H_{amb}) - T_{amb}\,(S - S_{amb}) + \ldots}$$

Where: H = Enthalpy, S = Entropy, T_{amb} = Ambient Temp. , S_{amb} = Ambient Entropy

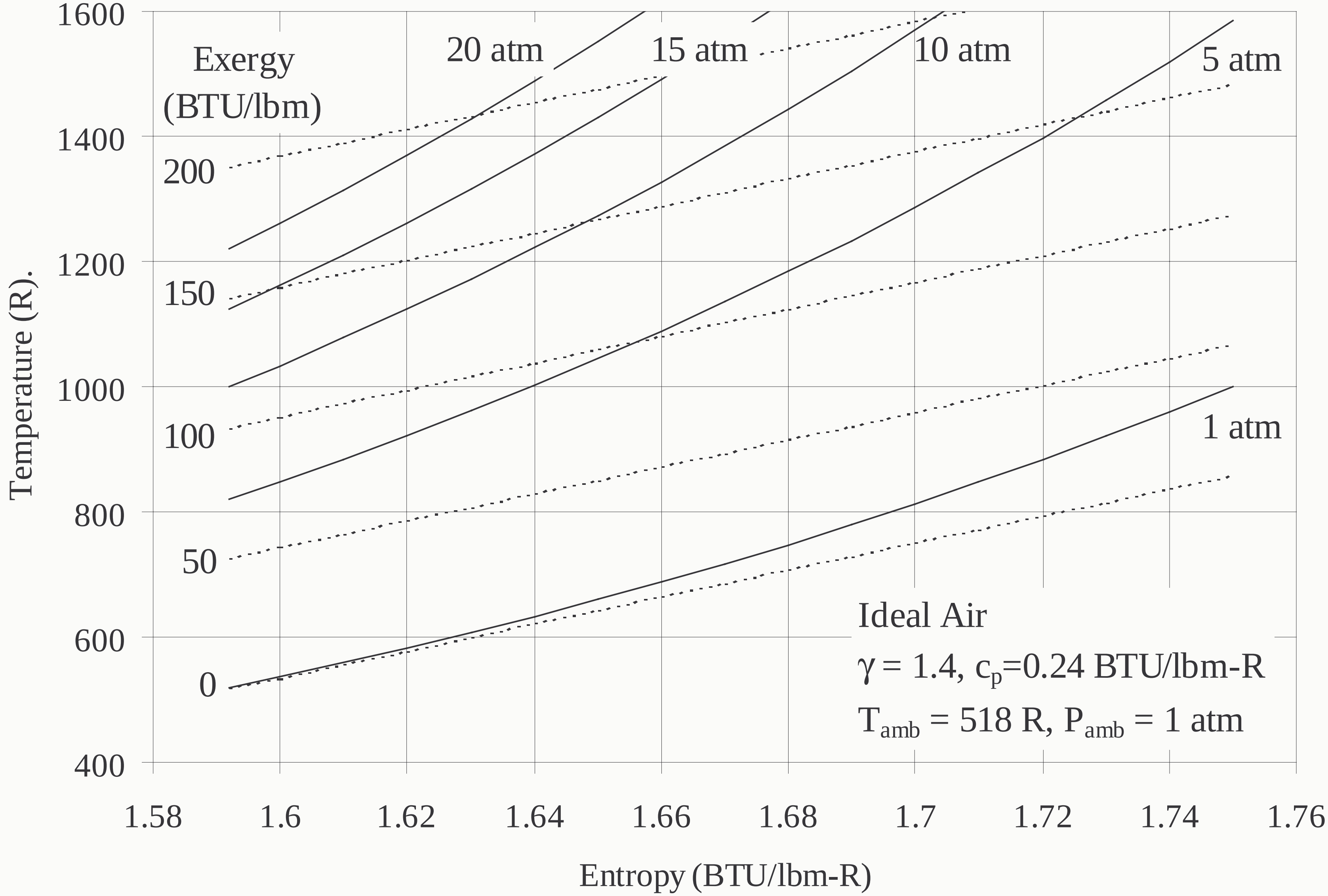
- Exergy is a state, just like temperature, pressure, etc.
- Requires the application of the first and second laws
- Energy is conserved; exergy is not - it can be destroyed (entropy increase)
- Must specify the ambient (reference) environment
- Floating reference environment for aerospace applications

Definition of Exergy (ctd)

- Ex = 0 plots as a line passing through H_{amb}, P_{amb} with slope T_{amb}
- Note that Ex = f(T,P)



Exergy for Ideal Air



Development of Exergy for Propulsion Design

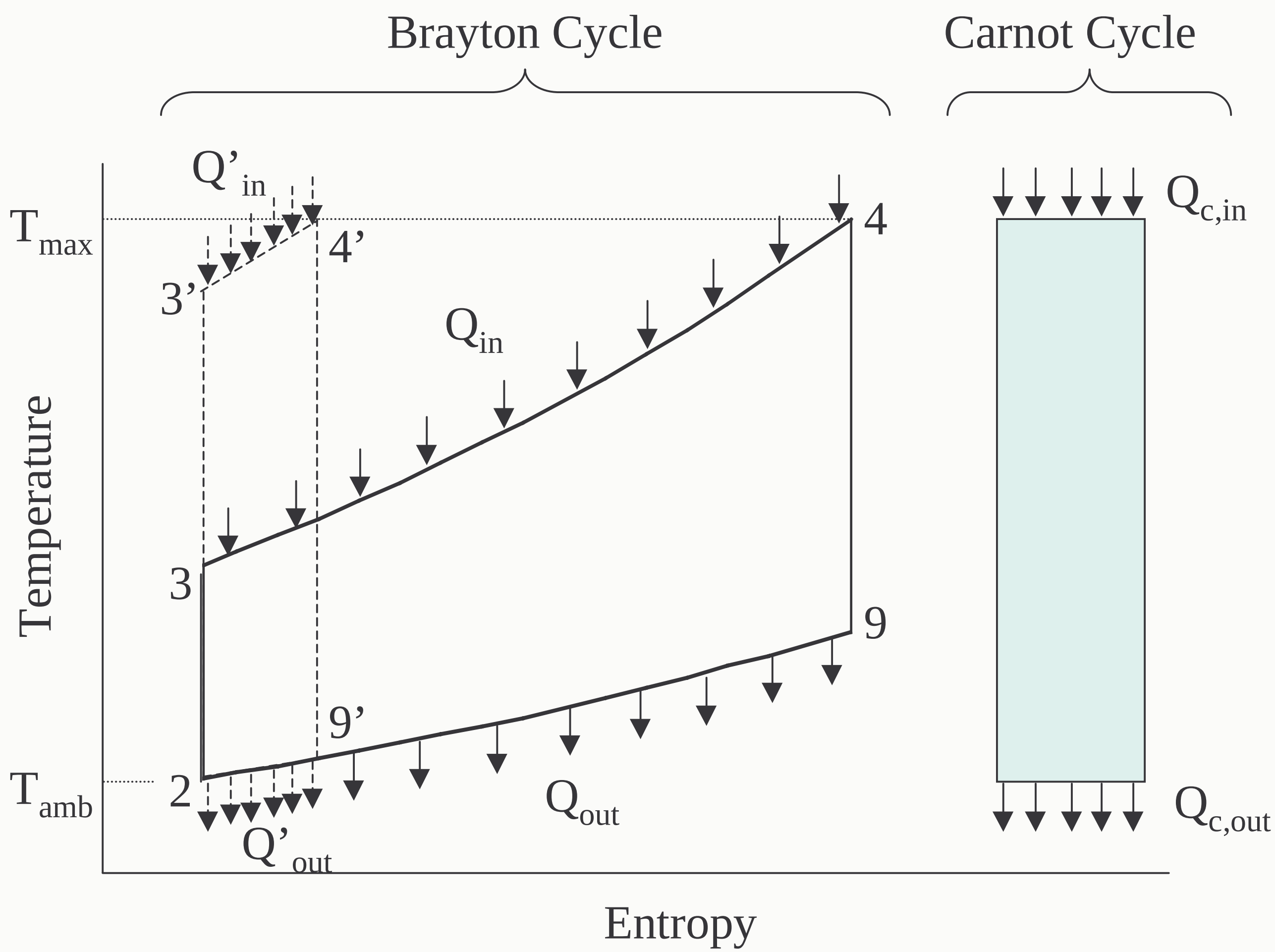
- Exergy concepts have not found acceptance or significant application in the aerospace industry
  - No perceived need to use in cycle analysis; 1st law + Newton's + continuity is sufficient to get temp., pressure, flow rates, work, etc; nothing more needed
  - No perceived application for 2nd law concepts beyond cycle analysis (i.e.- perceived as a cycle analysis tool only, no relevance to mission analysis, weight & flowpath, mechanical design, or cost)
- Significant work published in application of second law concepts to ground-based power systems
- Some work in academia towards application of 2nd law to hypersonic propulsion systems, driven by:
  - Need to minimize losses (which can easily become exorbitant for hypersonic propulsion systems)
  - Need to consider performance of combined engine/airframe
  - Need for a uniform means of bookkeeping losses and comparing them on an equal basis

Terms in General Exergy Equation*

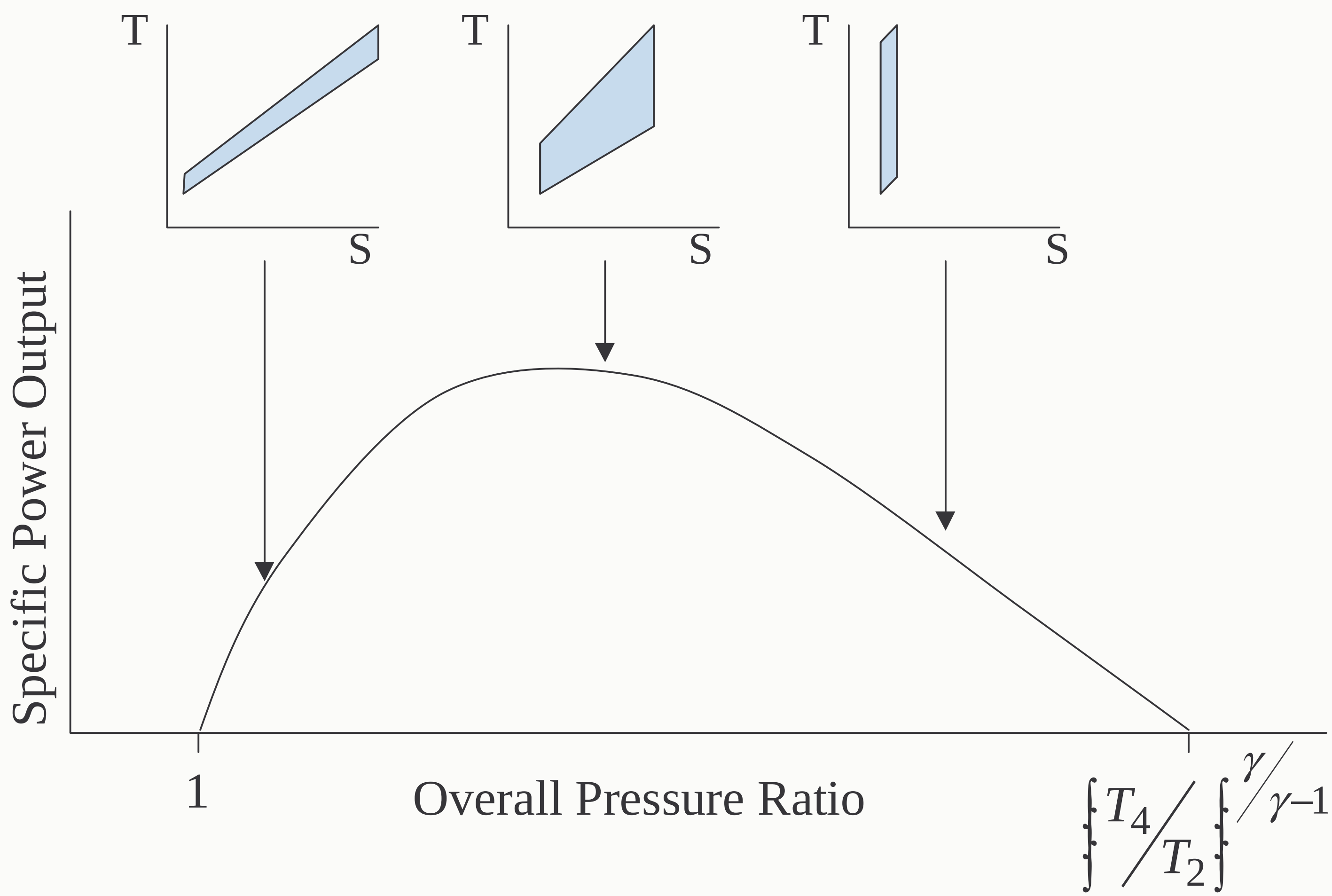
Process Type	*Driving Potential*	*Flow Charge*	*Entropy Change*	*Exergy Term*
Heat Flow	Temp. Diff.	Heat	dQ/T	$T_0 dQ/T$
Electrical	Voltage Diff.	Current, I	I^2R/T	$T_0 I^2R/T$
Flow Momentum	Velocity Diff.	Mass Flow	$c_i(v_i^2-v_0^2)/2gJT$	$T_0 c_i(v_i^2-v_0^2)/2gJT$
Gravity	Altitude Diff.	Mass	$m(z_2-z_1)g/Jg_c$	$T_0 m(z_2-z_1)g/Jg_c$
Thermoelectric	EMF	Heat + I	$dQ/T+I^2R/T$	$T_0[dQ/T+I^2R/T]$
Friction	Pressure Drop	Mass	$(P_2-P_1)/J$	$T_0(P_2-P_1)/JT$
Melting, Freezing	Enthalpy Diff.	Phase Ch.	$\Delta h/T$	$T_0\Delta h/T$
Chemical Rxn	Chem. Potential	Heat, Q	$N_i(\mu_{i,1}-\mu_{i,0})$	$T_0 N_i(\mu_{i,1}-\mu_{i,0})/T$
Radiation	Stephan-Bolt.	Heat, Q	$\varepsilon AF\sigma(T_1^4-T_0^4)$	$\varepsilon AF\sigma(3T_1^4-T_0^4-4T_0T_1^3)$
Mixing (isothermal)	Partial Press.	Mass	$R_i \ln(P_{i,2}/P_1)$	$T_0 R_i \ln(P_{i,2}/P_1)$

* Taken from Ahern, *The Exergy Method of Energy Systems Analysis*, Wiley, New York, 1980.

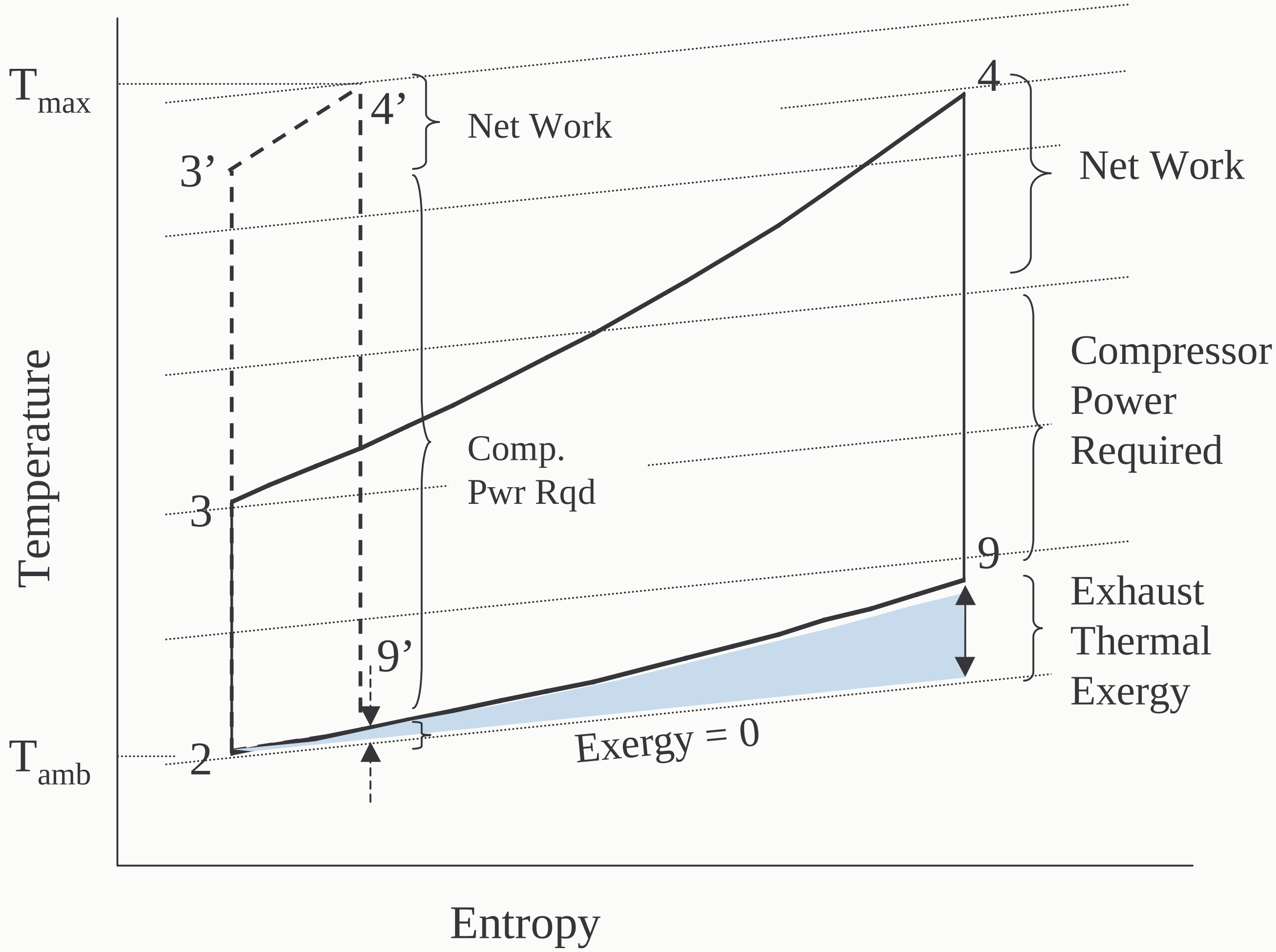
Classical Presentation - Impact of Cycle Pressure Ratio



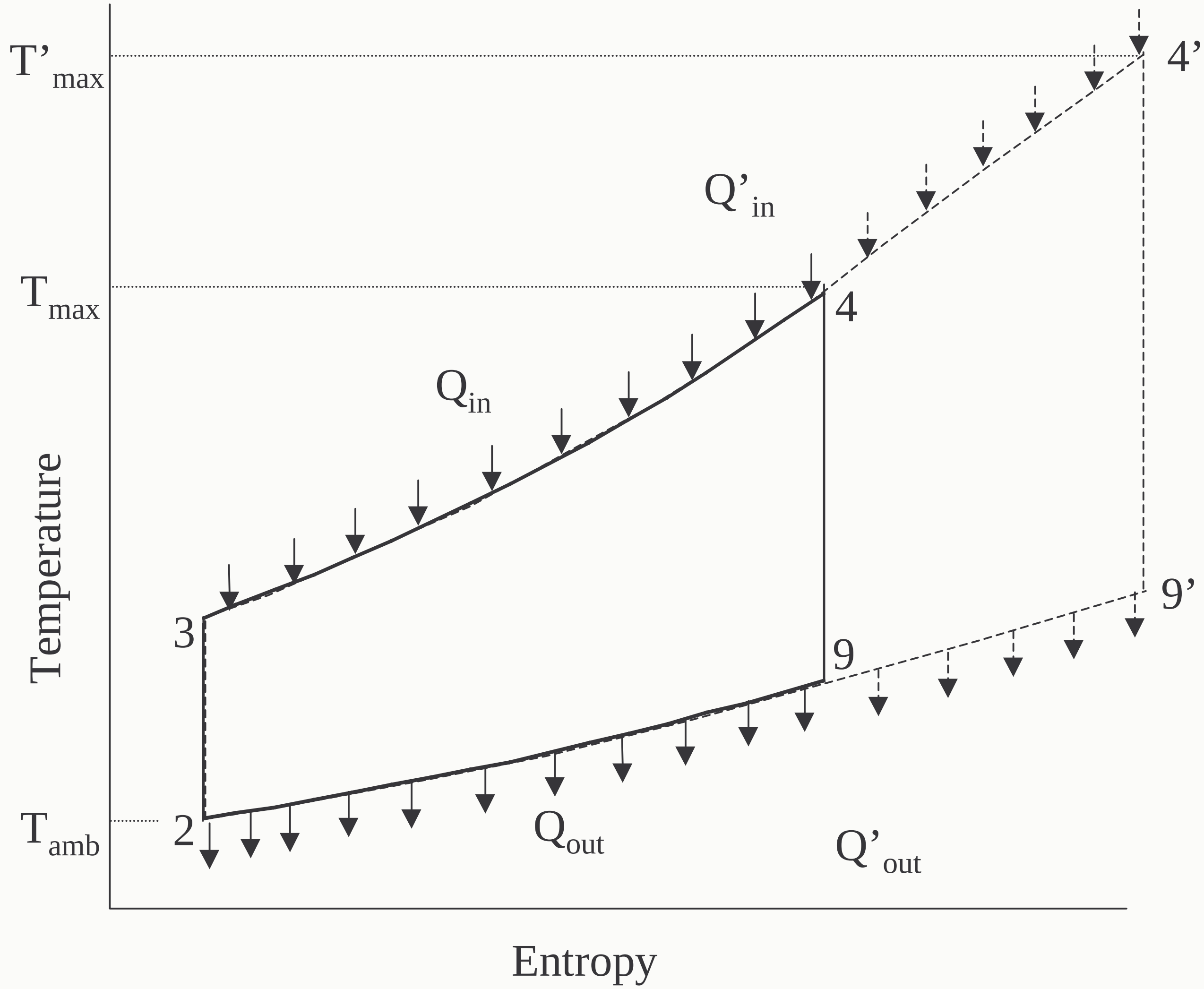
Impact of Cycle Pressure Ratio (ctd)



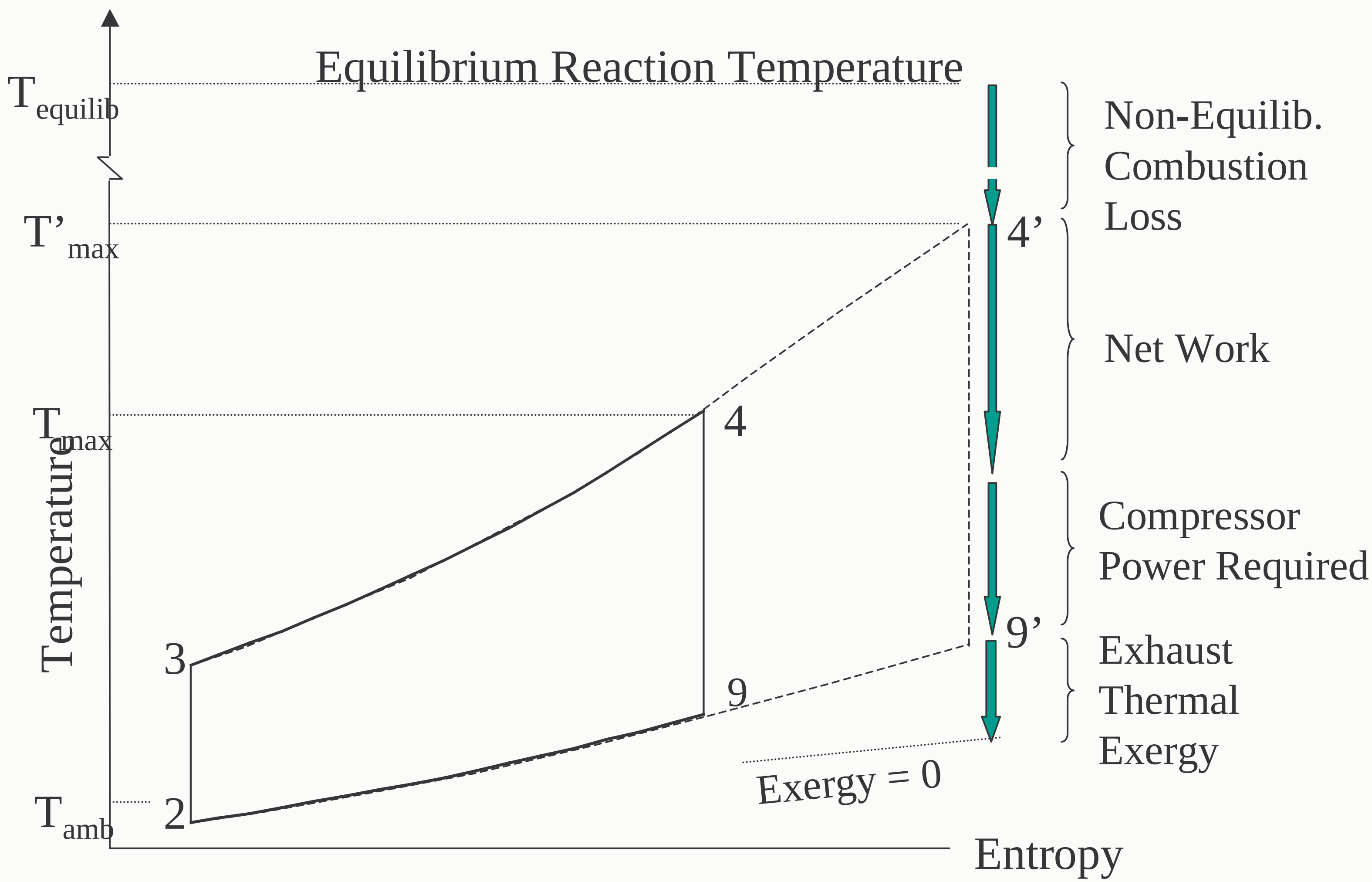
Work Availability Presentation - Cycle Pressure Ratio



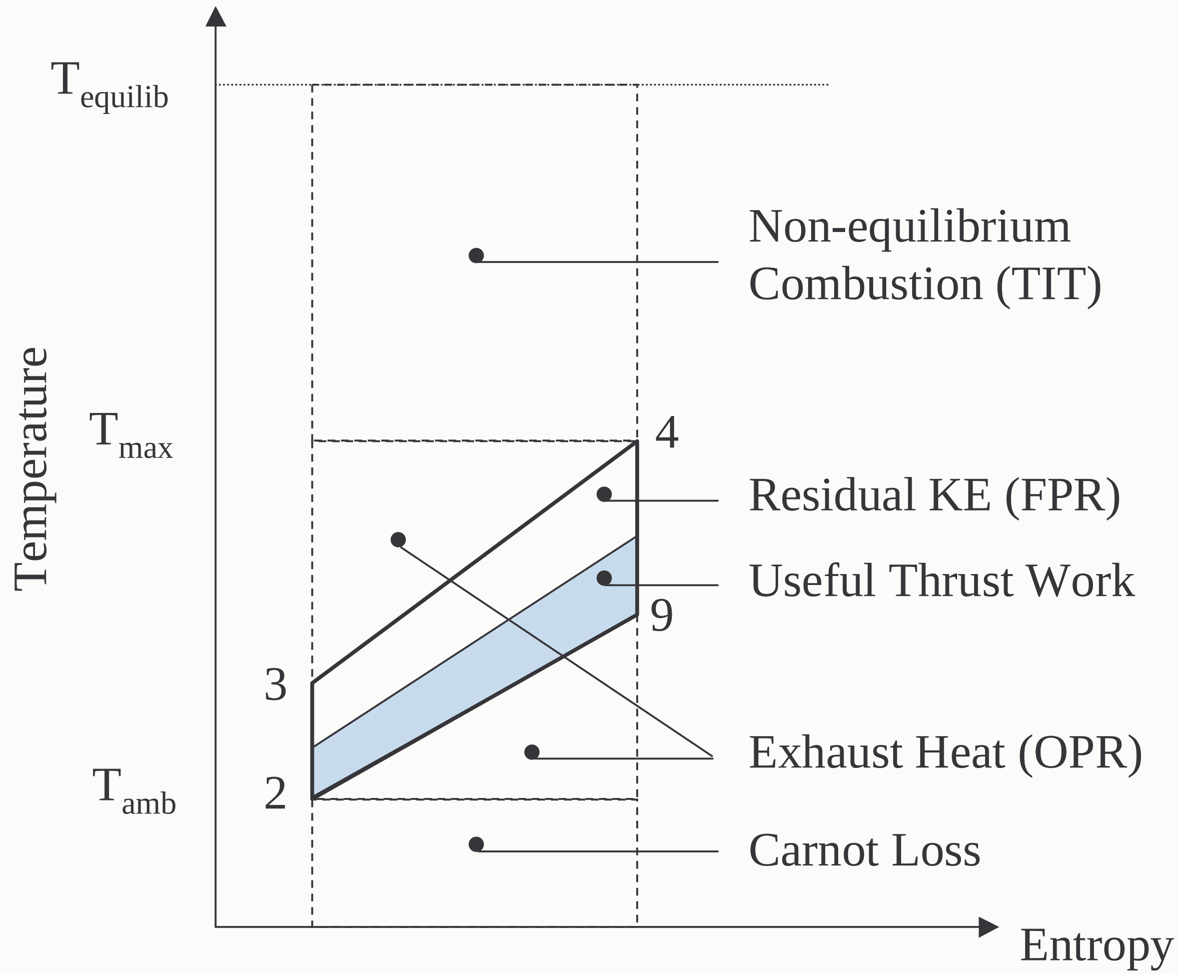
Classical Presentation - Impact of TIT



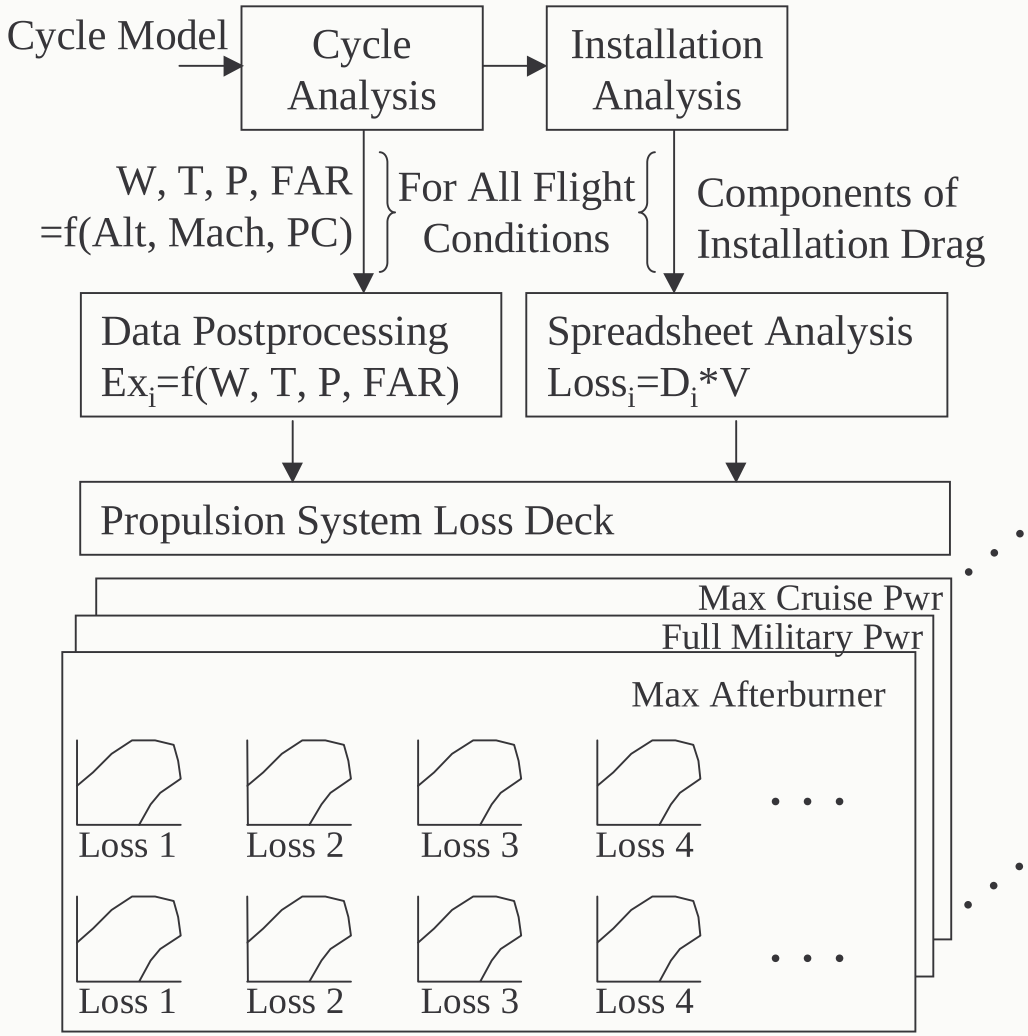
Work Availability Presentation - TIT



Summary: Work Availability Perspective

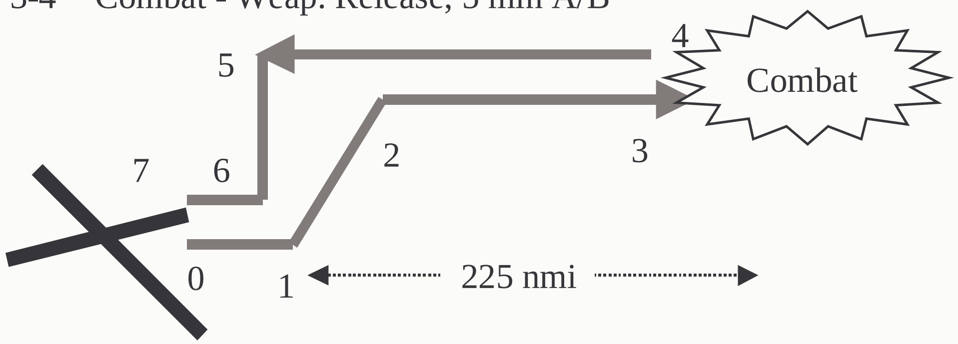


Method for Detailed Loss Estimation



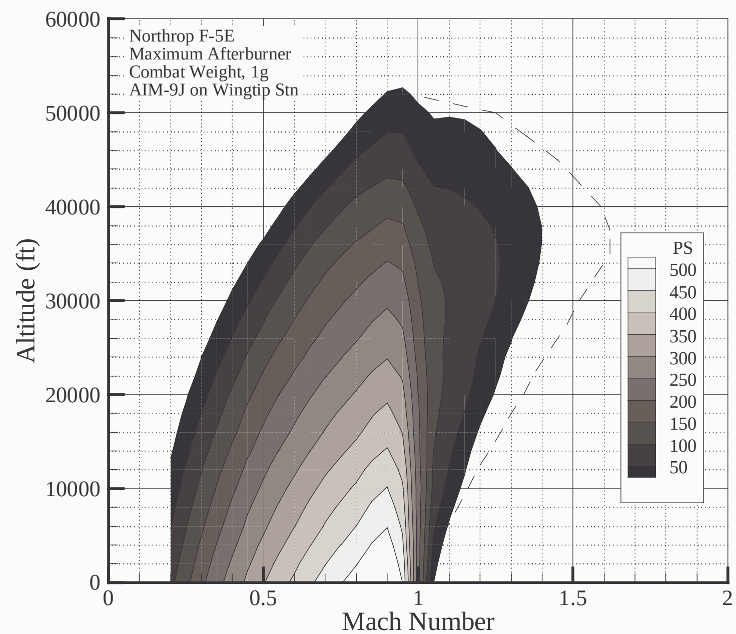
F-5E Aircraft and Design Mission

Leg	Description	Leg	Description
0-1	Warm-up, Taxi, Takeoff	4-5	Return to base BCA/M
1-2	Climb to BCA	5-6	Descent, 20 min Loiter
2-3	Cruise 225 nmi at BCA/M	6-7	Land w/ 5% Reserve
3-4	Combat - Weap. Release, 5 min A/B		

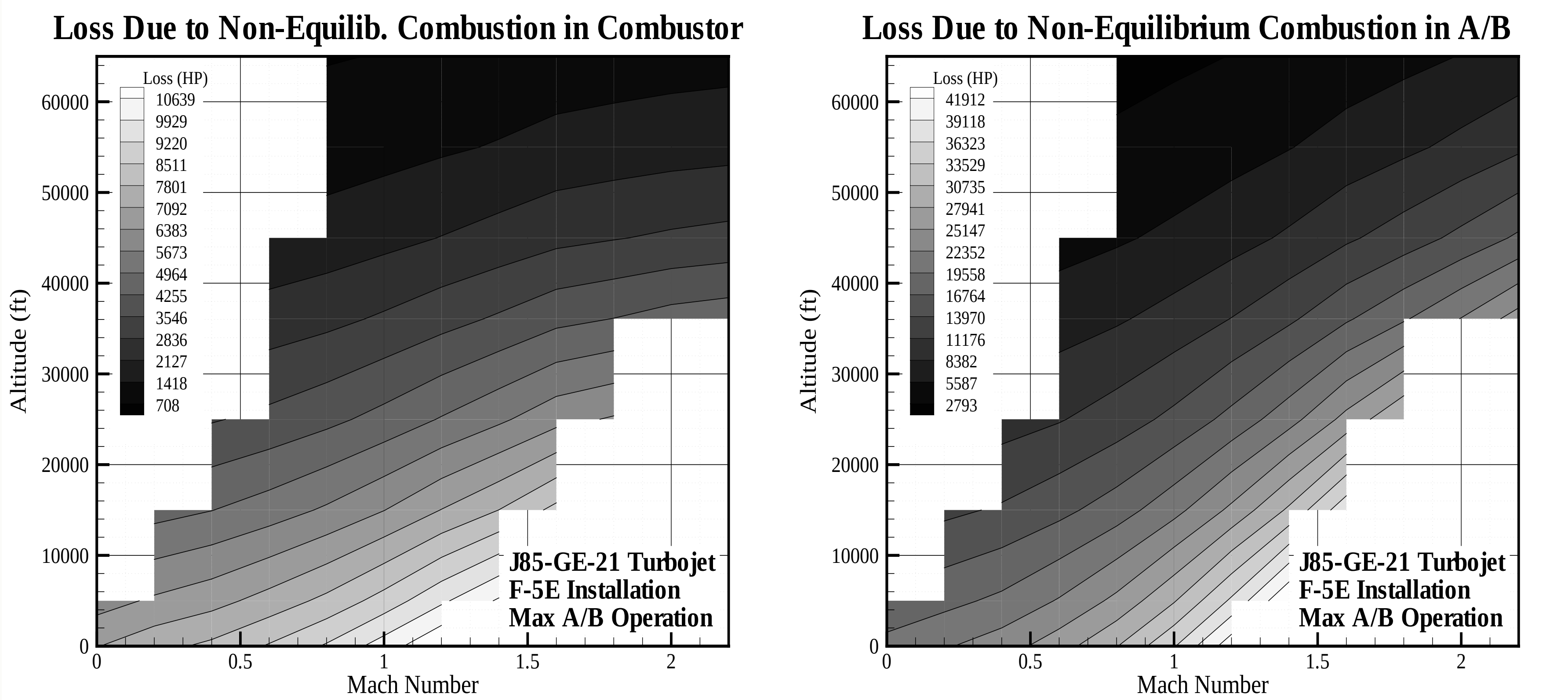


Mission Assumptions and Allowances

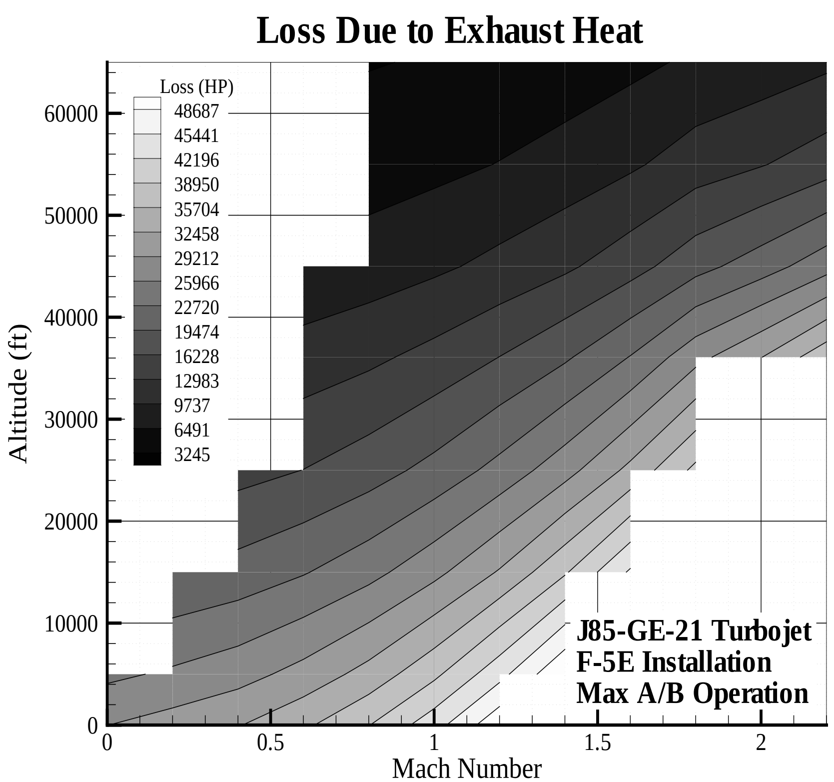
Takeoff: 1 min @ A/B
Climb: 2 min @ Full Military Power
Cruise: BCA/M
Combat: Climb on Course to 50K, Fire Missiles, 5 min A/B, No Range Credit
Cruise: BCA/M (No Range for Descent)
Reserve: 20 Minutes Loiter + 5% Fuel
Other: 5% Fuel Flow Conservancy

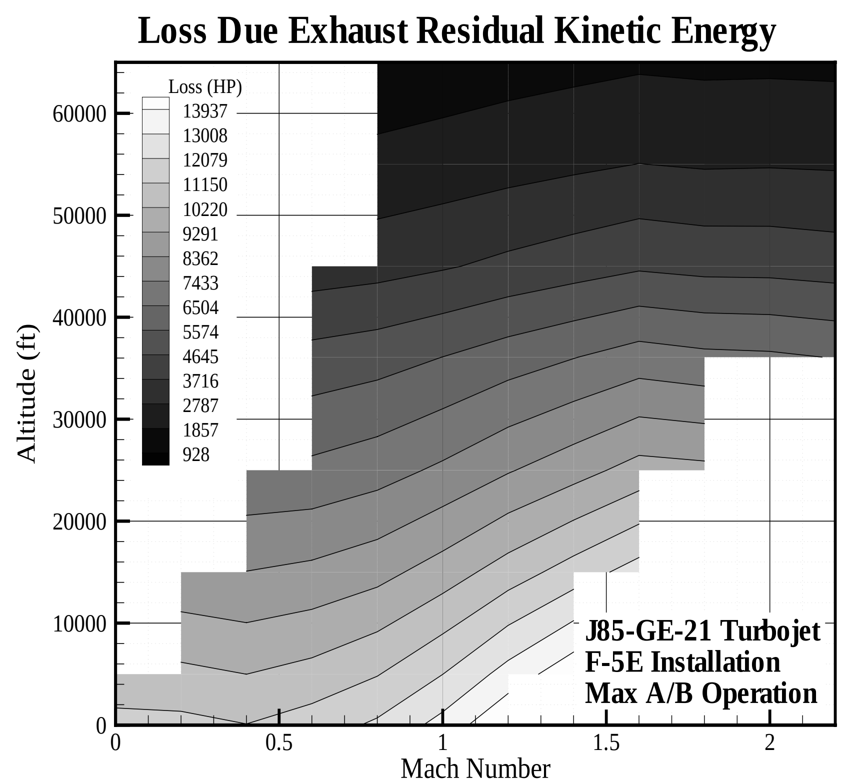


Losses due to J85-GE-21 Cycle

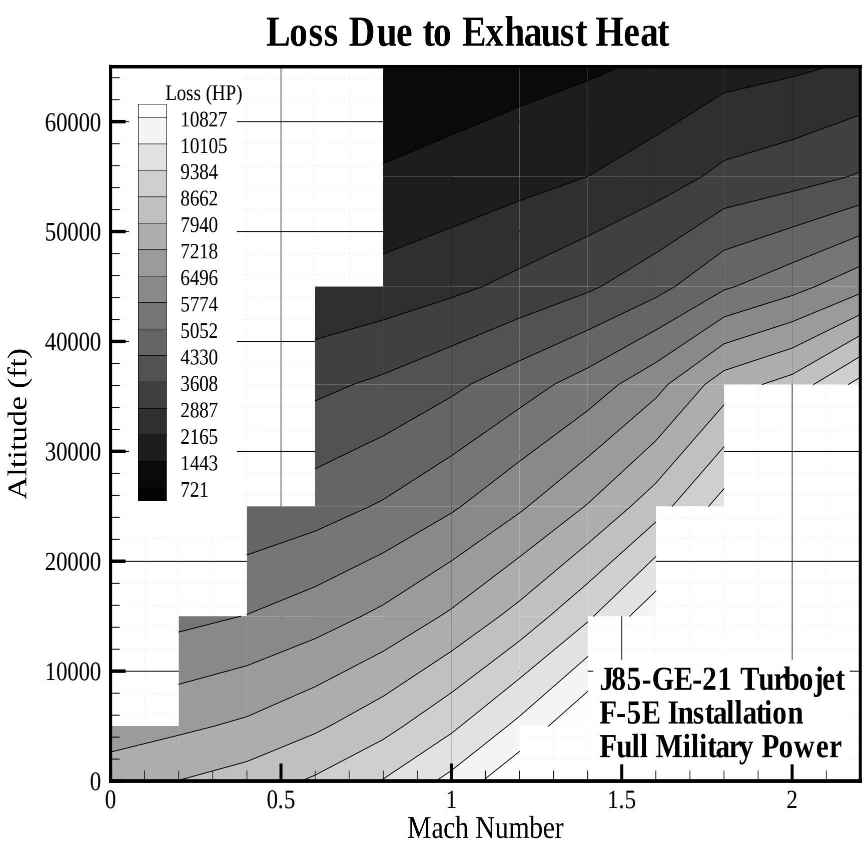


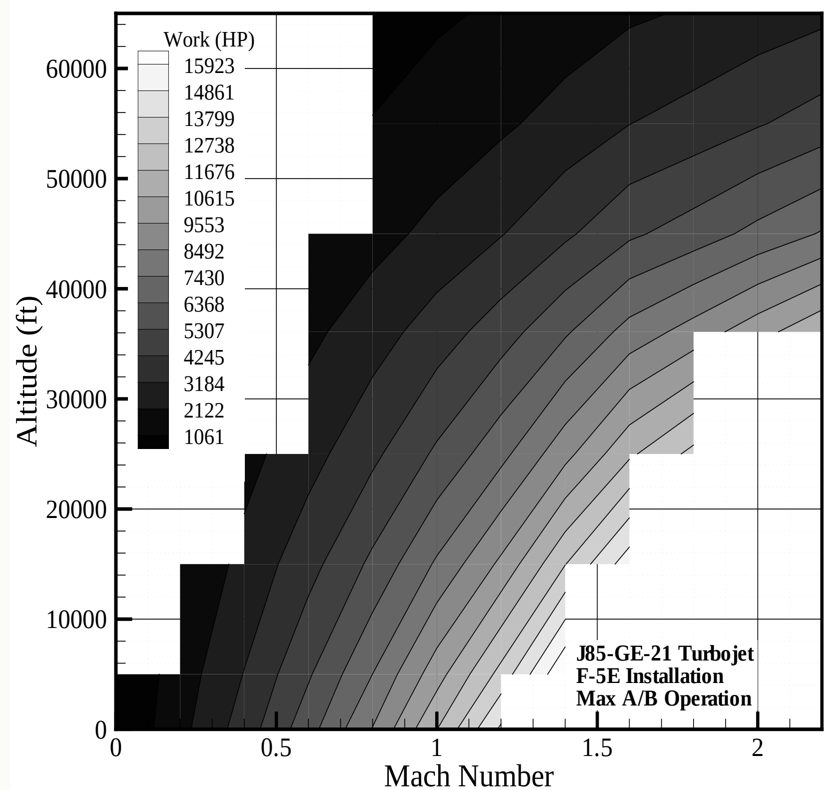
Losses due to J85-GE-21 Cycle (ctd)



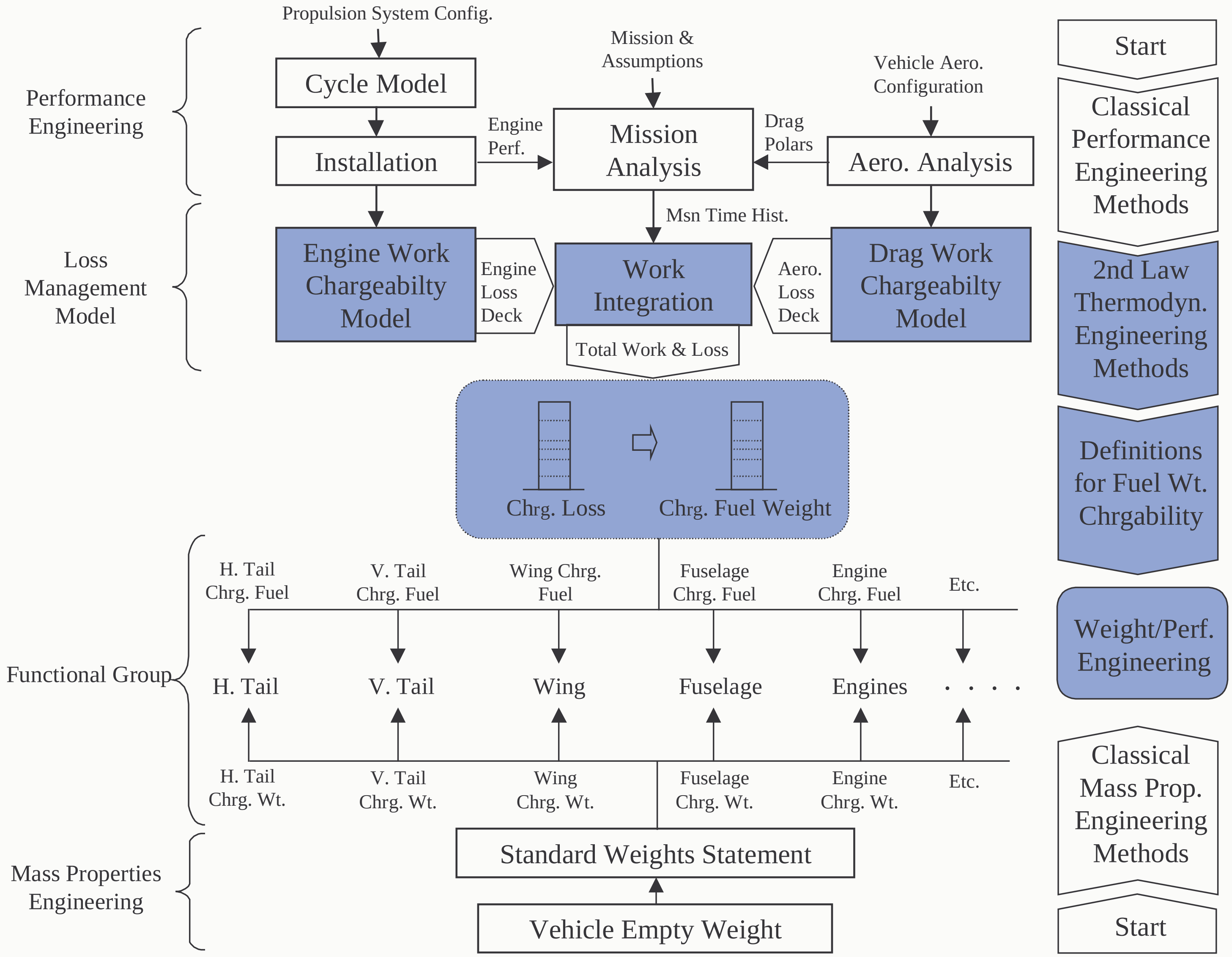


Losses due to J85-GE-21 Cycle (ctd)





Loss Management Models in Vehicle Design



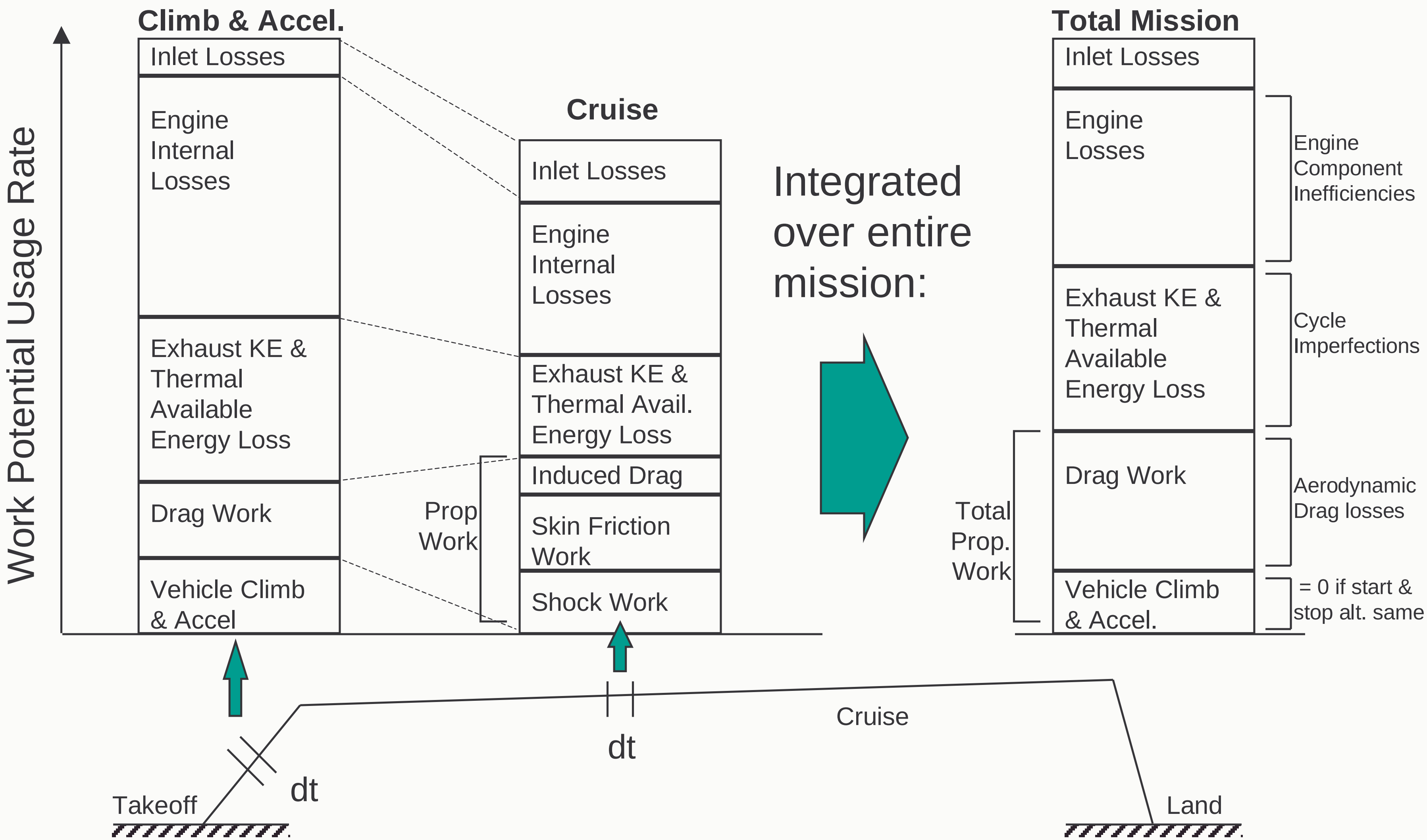
Conclusions

- Loss management methods provide information above and beyond classical analyses
  - Describe *how* each loss mechanism is impacted by technologies
  - Translatable into chargeable fuel weight
- Allows comparisons of technology on an “apples to apples” basis
- For the F-5E, 90% of all exergy usage is chargeable to the propulsion system
  - Much to be gained by continued emphasis on enabling technologies that allow improved cycle (OPR and TIT)
  - Same situation still applies for today’s engines

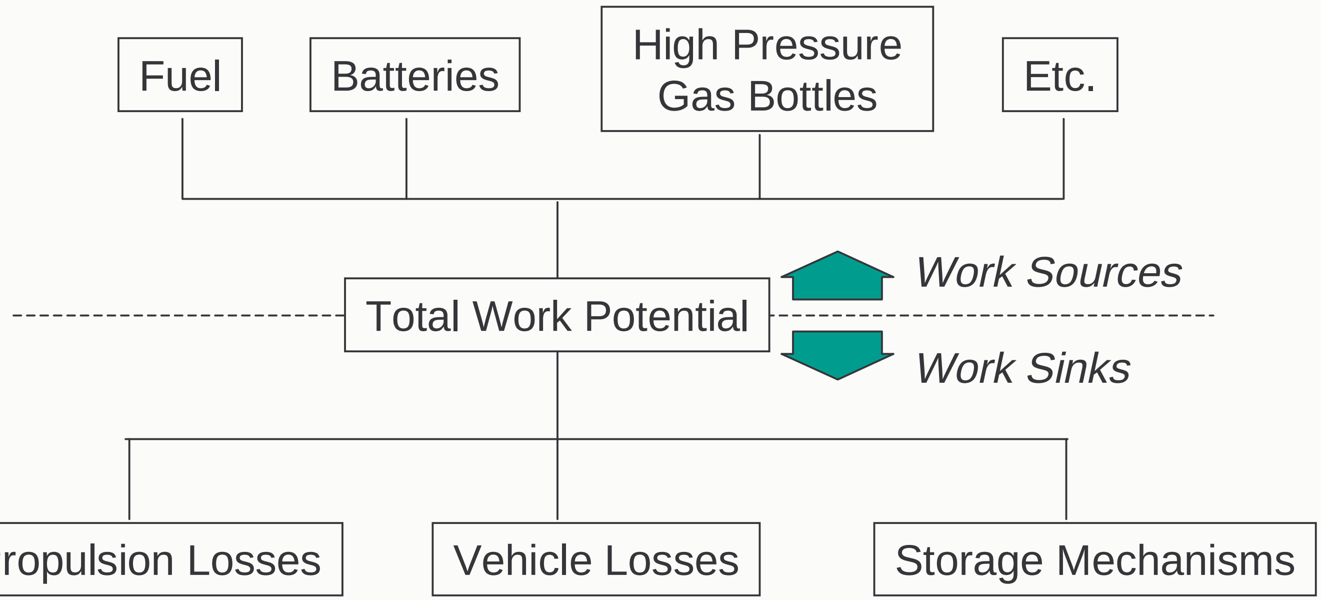
Summary

- From an aerothermodynamic standpoint, the objective of vehicle design is to *minimize total loss*
- The ability to discern the individual components contributing to loss is a step towards their conquest
- Particularly important for vehicles where thermodynamic loss is a major driver:
  - High speed aircraft
  - High delta-V vehicles (rockets)
- Allows "apples-to-apples" comparisons/trades between weight and performance
- Loss management models offer a powerful means to understand the link between *aerothermodynamic performance* and *vehicle mass properties*
- Loss management methods make it possible to *analytically calculate* individual components that make up the *cost* of each design decision
- If per-trip costs are integrated through life of airframe, one obtains LCC of performance losses
- Loss management approach facilitates evaluation of technology impact in a systematic and reasonable way
- Provides the foundation on which risk management methods can be developed

Loss Accounting in Vehicle Design



Typical Contributors to Vehicle Loss



Propulsion Losses

- Friction
- Fluid Dynamic Drag
- Heat Transfer
- Exhaust Heat
- Non-equilib. Combust.
- Exhaust Residual KE
- etc.

Vehicle Losses

- Friction
- Fluid Dynamic Drag
- Heat Transfer
- Molecular Diffusion
- Chemical Non-equilib.
- etc.

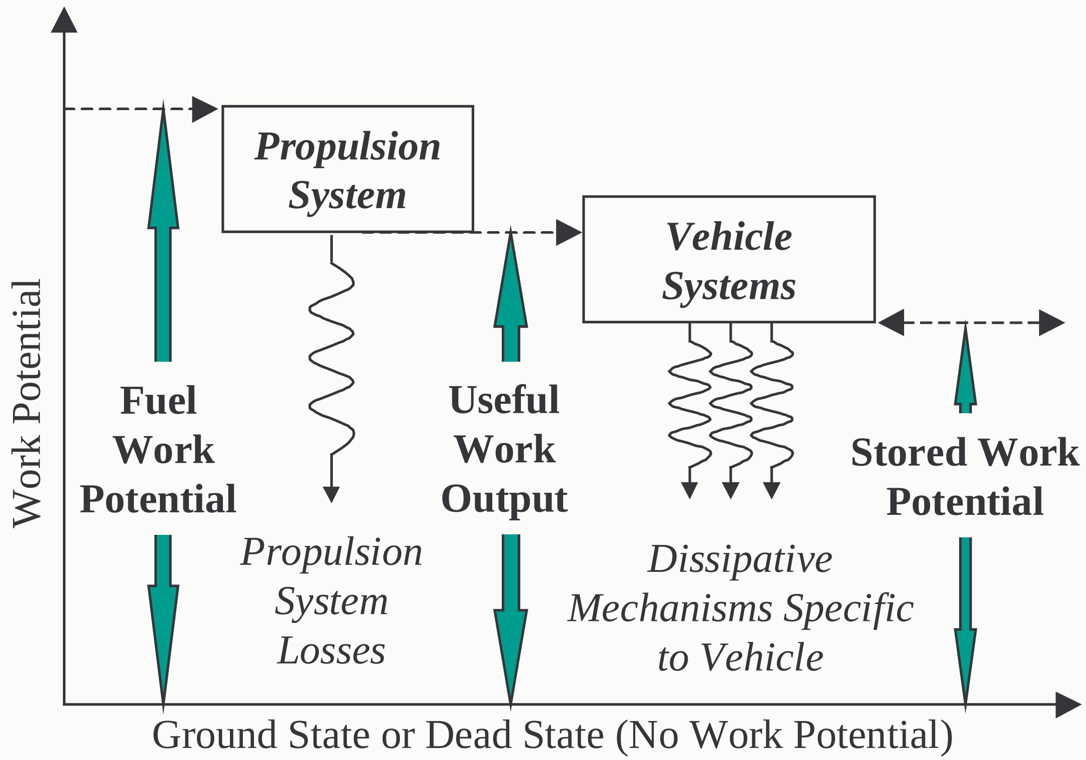
Storage Mechanisms

- Kinetic Energy (KE)
- Potential Energy
- Rotational Energy
- Heat Storage
- Batteries
- etc.

Loss Accounting Models

- ***Loss management model***: a comprehensive, system-wide vehicle thermodynamic model that accounts for usage of work potential amongst all vehicle systems and processes
- This idea is the centerpiece for a step-by-step development of a generalized loss management methodology applicable to any automotive system

Generalized Model of Work Potential Consumption



$$(\text{Initial Work Potential}) = (\text{Propulsion System Losses}) + (\text{Vehicle Losses}) + (\text{Final Work Potential})$$

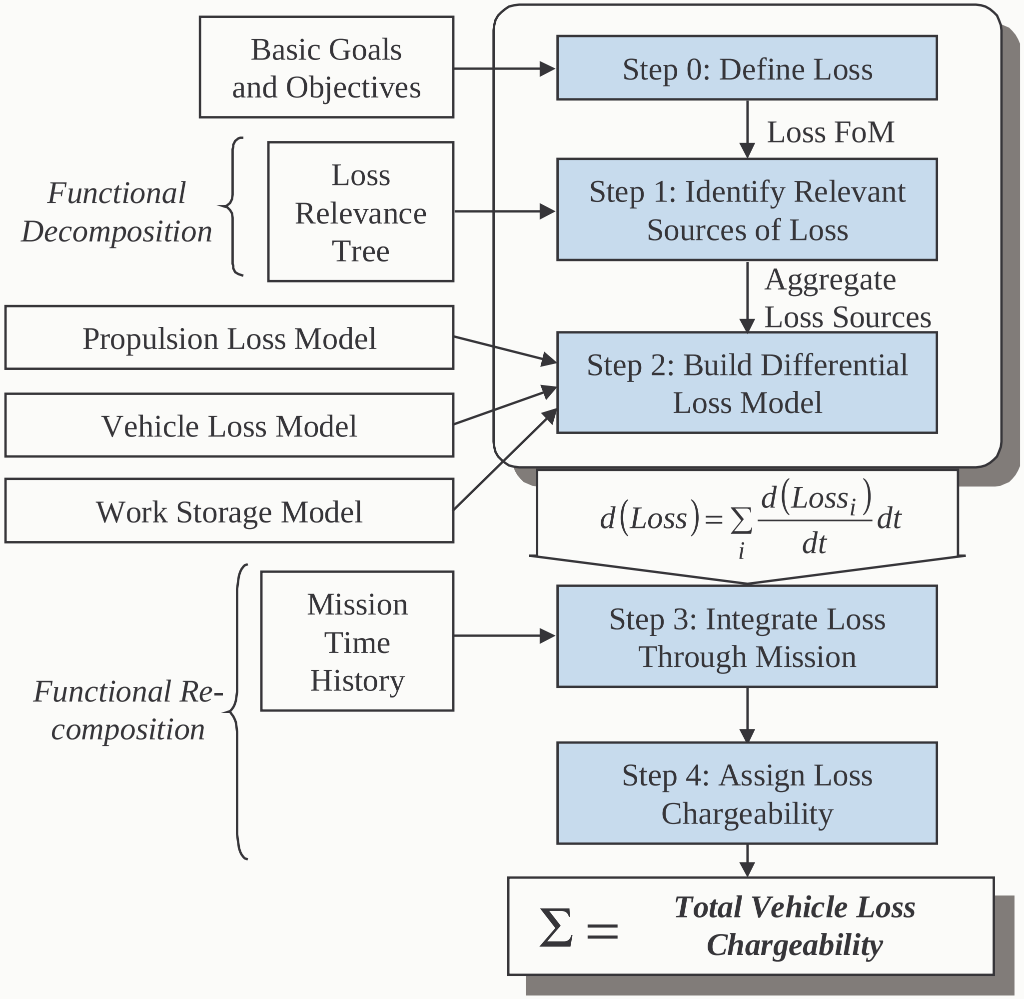
or

$$(\text{Work Potential Consumed})\Big|_0^t = \int_0^t \sum_i \frac{(\text{Propulsive Loss})_i}{dt}dt + \int_0^t \sum_j \frac{(\text{Vehicle Losses})_j}{dt}dt + \int_0^t \sum_k \frac{(\text{Stored Potential})_k}{dt}dt$$

Loss Management Methodology

Contributing Elements

Loss Model*: *differential representation of loss as a function of vehicle operating condition

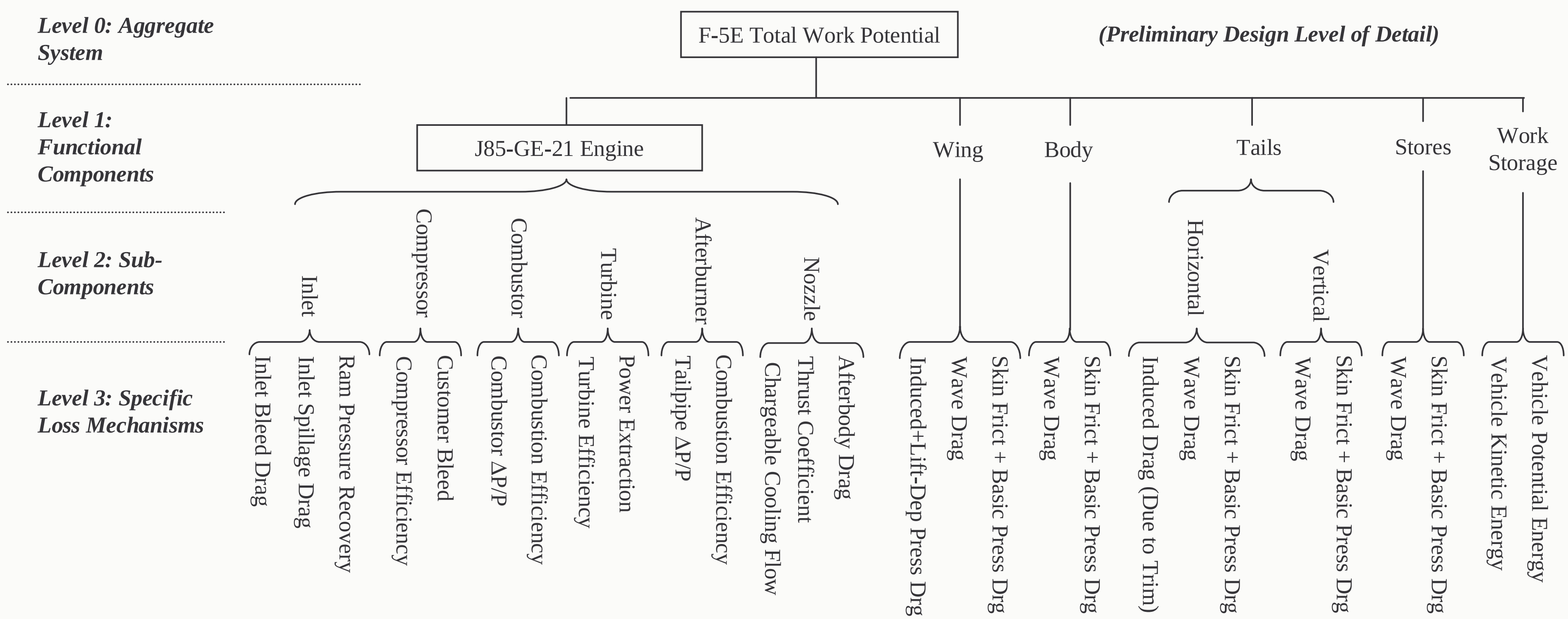


Key Questions:

- What is the FoM of ultimate interest?
- What constitutes a loss?
- How can it be quantified?
- What level of detail is required?
- What are the relevant sources of loss?
- How are propulsion losses best modeled?
- How are vehicle losses best modeled?
- What is the nominal mission of interest?
- What factors are driving loss?
- How do they impact the design?

Step 1: Identify Relevant Loss Sources

(Northrop F-5E)

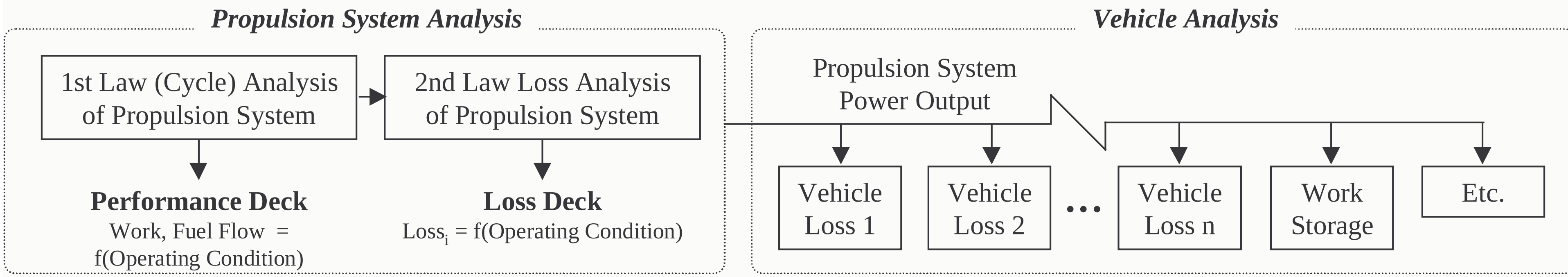


Step 2: Develop Differential Loss Mgm't Model

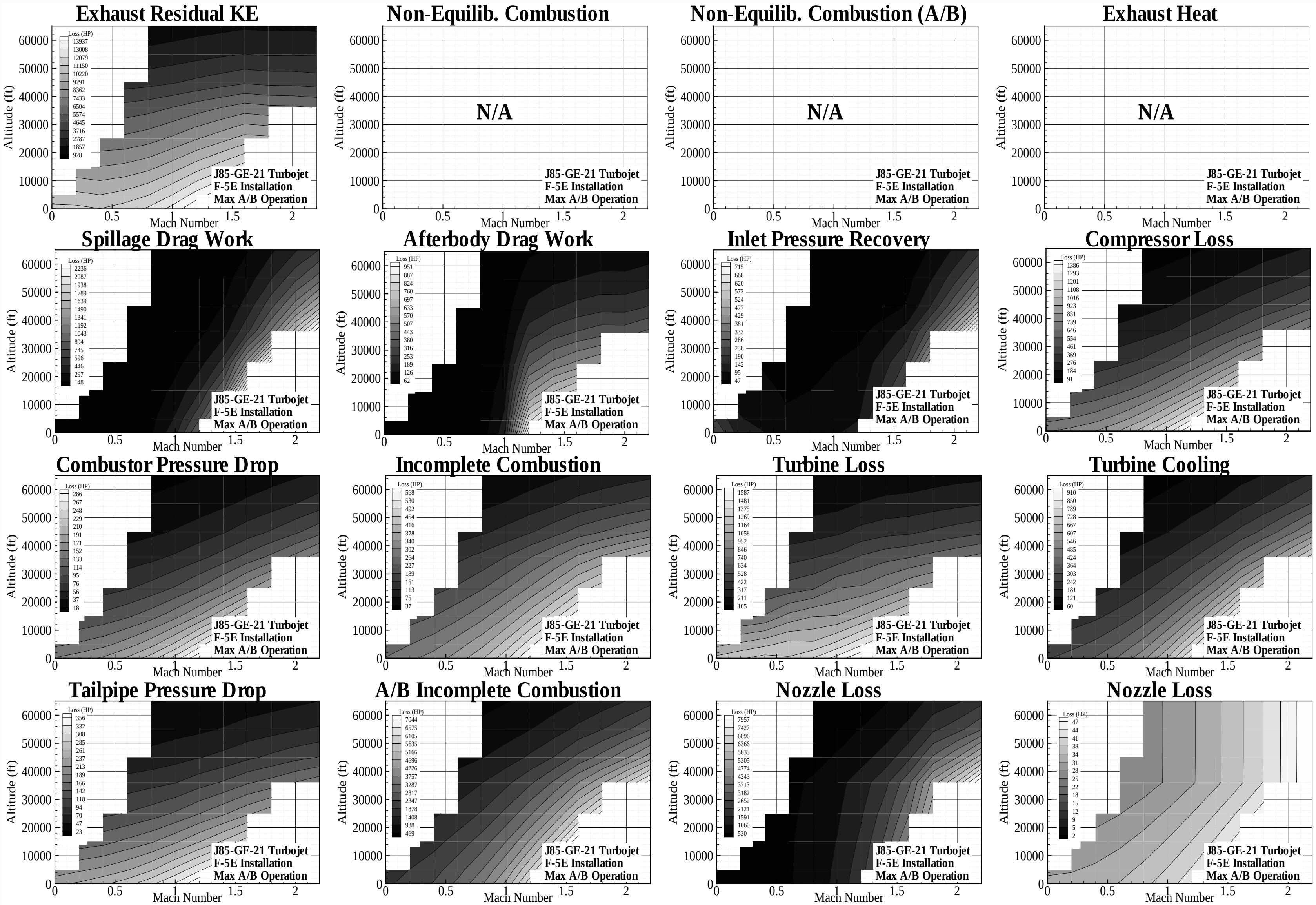
- Objective: to develop a differential representation of total vehicle loss that can be integrated through time to yield the total loss
- This differential representation has the form:

$$d(\text{Total Loss}) = \sum_i \frac{d(\text{Loss}_i)}{\text{dt}} dt$$

- Loss_i = f(Alt, Mach, Power Setting, Ambient Conditions)

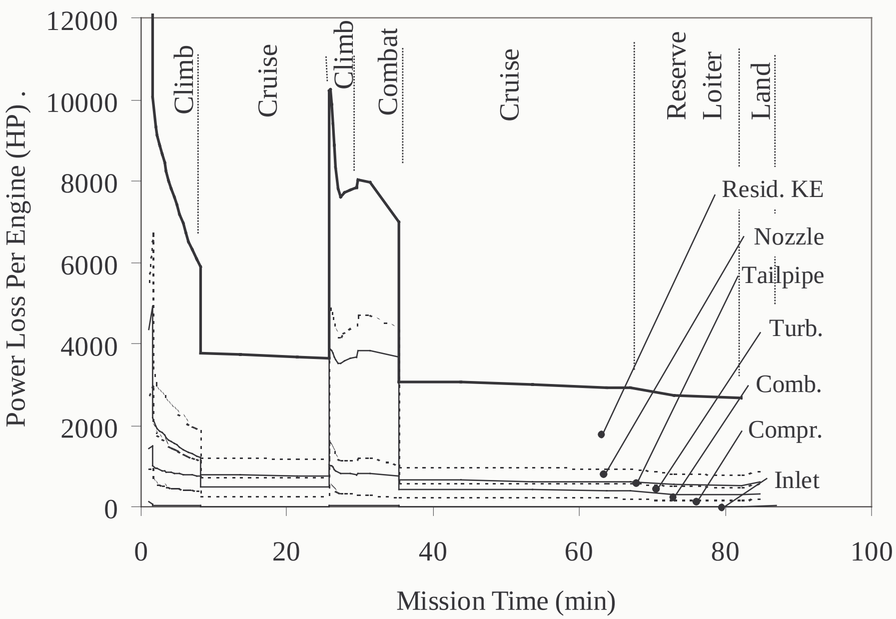


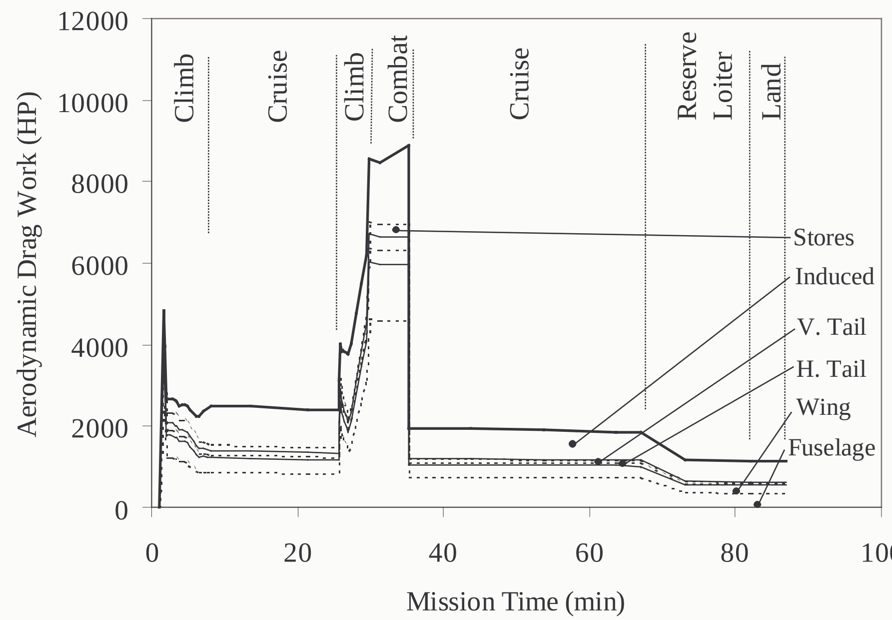
Typical F-5E Propulsion Loss Deck



Step 3: Integrate Loss Through Mission

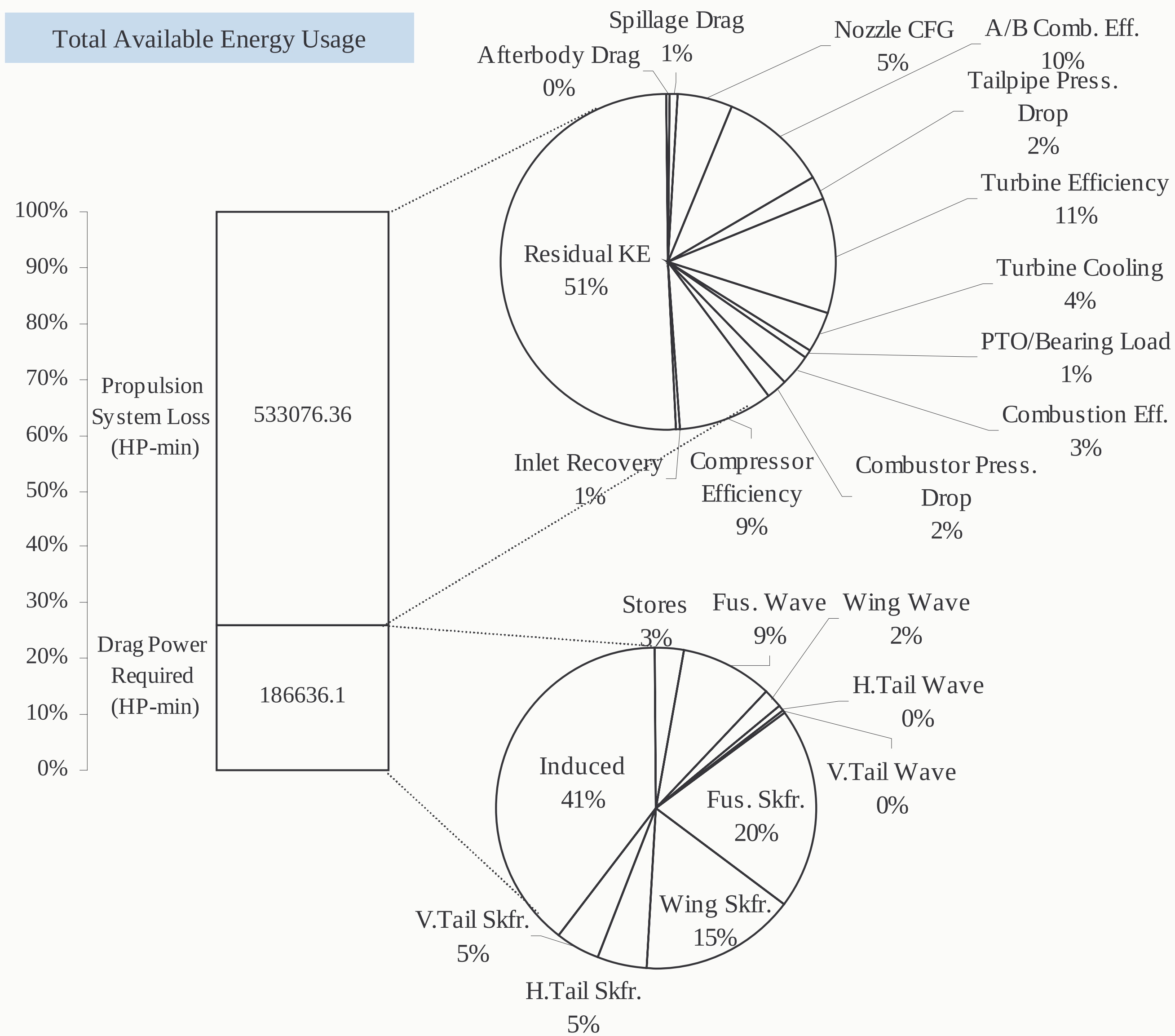
- Use mission time history in conjunction with aero & prop. loss decks to piecewise integrate usage of work potential through the mission:





Note: Power consumption measured in terms of "gas horsepower"

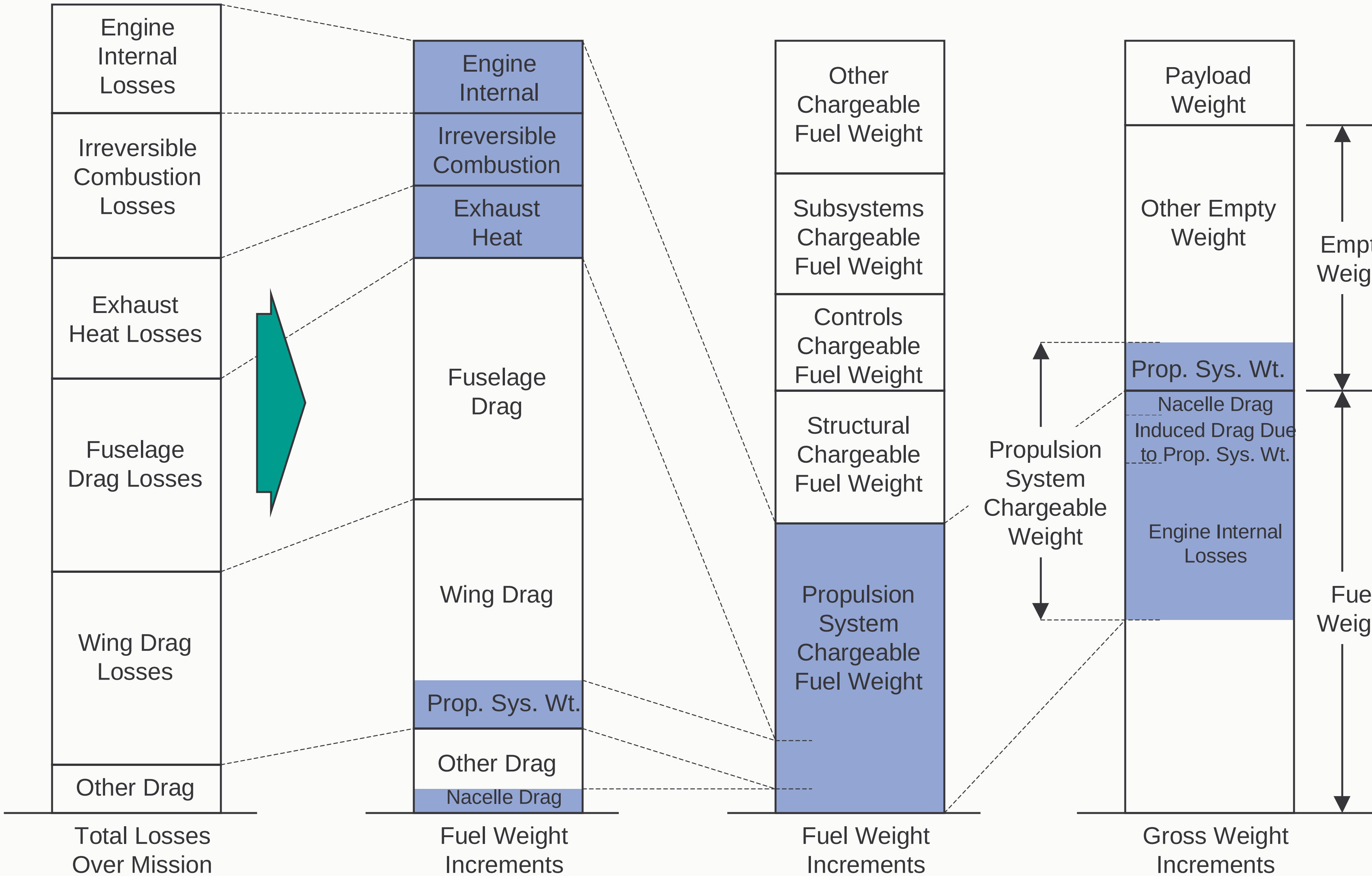
Step 3: Integrate Loss Through Mission (F-5E)

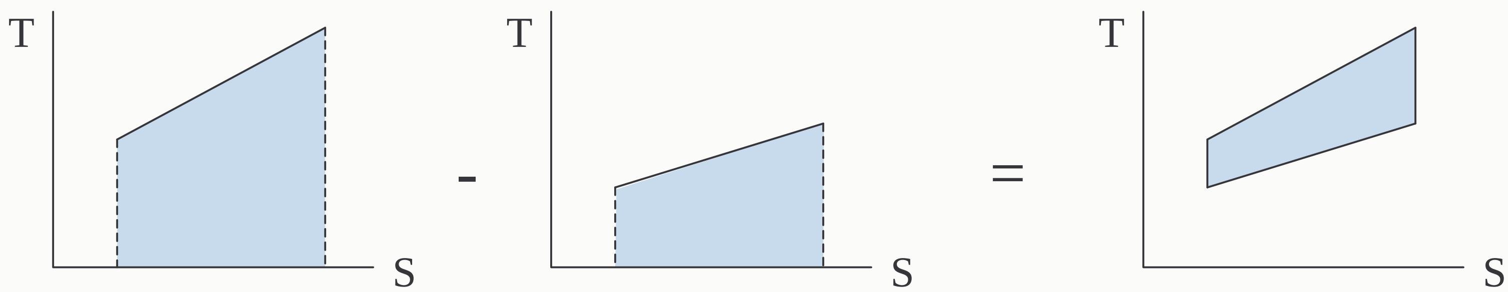


Link Between Performance & Weight

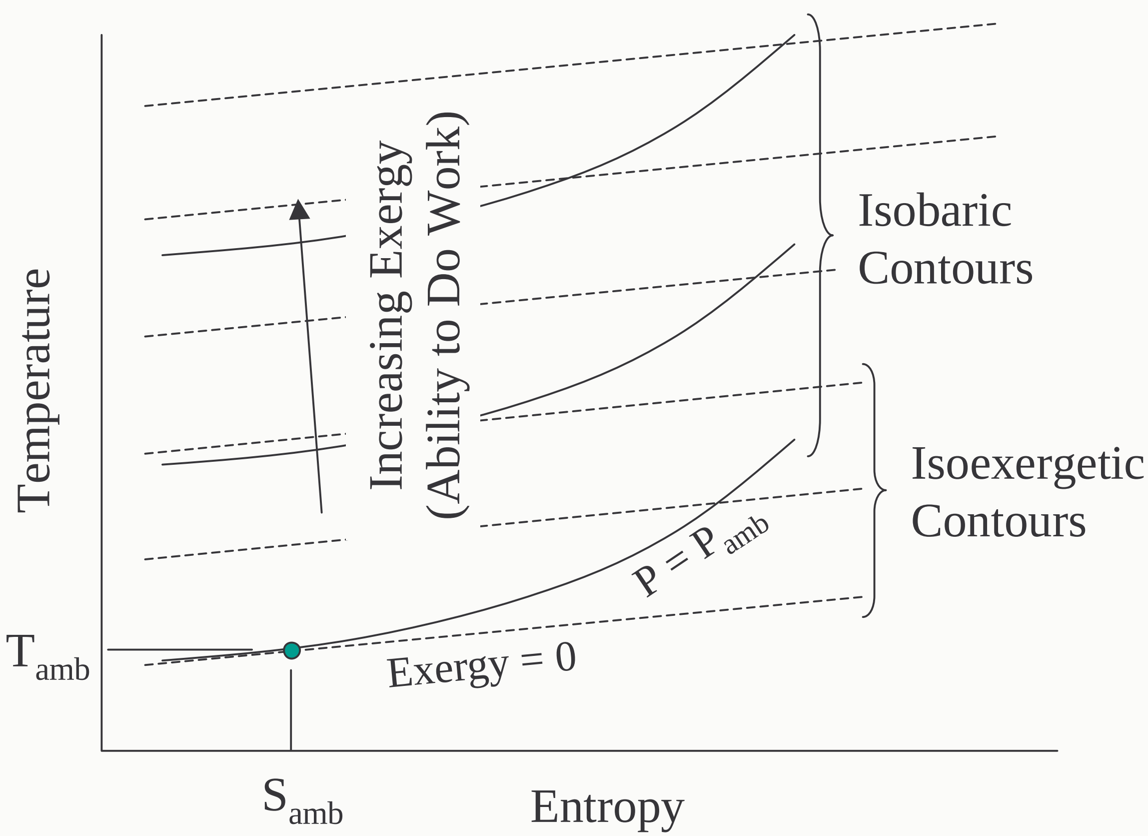
- The aerospace industry is more sensitive to vehicle weight than any other automotive industry
- The reason: vehicle weight is a strong driver on losses
- Yet, the fundamental relationship between aerothermodynamic performance and vehicle weight is *not* well-understood
- **One can show that both aerothermodynamic performance and weight aspects of design can be quantified in terms of *chargeable gross weight***

Vehicle-Level Gross Weight Stack-Up

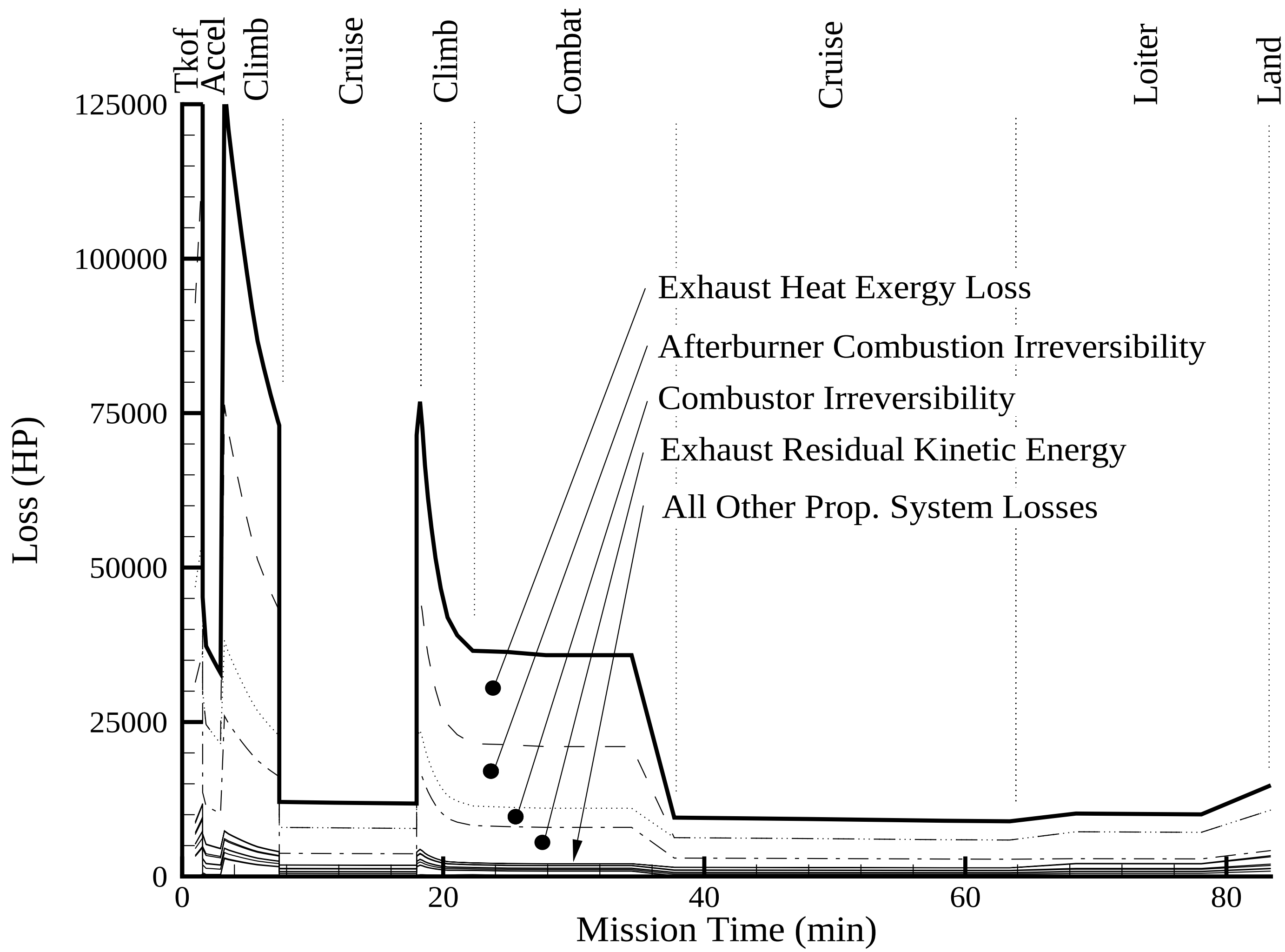




$$Q_{in} - Q_{out} = W_{out}$$


Temperature
Increasing Exergy
(Ability to Do Work)
Isobaric
Contours
Isoexergetic
Contours
P = P amb
T amb
Exergy = 0
S amb
Entropy

Propulsion System Exergy Usage (F-5E Design Mission)



Total Exergy Usage (F-5E Design Mission)