Risk-Based Probabilistic Approach to Aeropropulsion System Assessment

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In an era of shrinking development budgets and resources, where there is also an emphasis on reducing the product development cycle, the role of system assessment, performed in the early stages of an engine development program, becomes very critical to the successful development of new aeropropulsion systems. A reliable system assessment not only helps to identify the best propulsion system concept among several candidates, it can also identify which technologies are worth pursuing. This is particularly important for advanced aeropropulsion technology development programs, which require an enormous amount of resources. In the current practice of deterministic, or point-design, approaches, the uncertainties of design variables are either unaccounted for or accounted for by safety factors. This could often result in an assessment with unknown and unquantifiable reliability. Consequently, it would fail to provide additional insight into the risks associated with the new technologies, which are often needed by decision makers to determine the feasibility and return-on-investment of a new aircraft engine.

In this work, an alternative approach based on the probabilistic method was described for a comprehensive assessment of an aeropropulsion system. The statistical approach quantifies the design uncertainties inherent in a new aeropropulsion system and their influences on engine performance. Because of this, it enhances the reliability of a system assessment. A technical assessment of a wave-rotor-enhanced gas turbine engine was performed to demonstrate the methodology. The assessment used probability distributions to account for the uncertainties that occur in component efficiencies and flows and in mechanical design variables. The approach taken in this effort was to integrate the thermodynamic cycle analysis embedded in the computer code NEPP (NASA Engine Performance Program) and the engine weight analysis embedded in the computer code WATE (Weight Analysis of Turbine Engines) with the fast probability integration technique (FPI). FPI was developed by Southwest Research Institute under contract with the NASA Glenn Research Center.

The results were plotted in the form of cumulative distribution functions and sensitivity analyses and were compared with results from the traditional deterministic approach. The comparison showed that the probabilistic approach provides a more realistic and systematic way to assess an aeropropulsion system. In summary, the probabilistic methodology has the following advantages:

1. It provides decision-makers with a tool that allows them to assign priorities to needed technological developments and thus increase the likelihood that R&D investments will have high payoffs.
2. It provides insight into the risks associated with new technologies, which makes it easier for the decision-makers to determine the benefit and return-on-investment of a new aircraft engine.

3. It allows the decision-makers to detect problems early before they become critical. Because of this, risks can be mitigated accordingly and resources (time, R&D funding, etc.) can be used more wisely.

4. It quantifies the reliability of a new aircraft engine. As a result, risks can be mitigated early and catastrophic engine failure will be minimized.

5. The results from probabilistic assessment are more credible and reliable, because it incorporates the 'past lessons learned' (i.e., expert opinions, historical data, etc.) to quantify the risks. As a result, the likelihood of repeating past mistakes will be minimized.

The current work addressed the application of the probabilistic approach to assess specific fuel consumption, engine thrust, and weight. Similarly, the approach can be used to assess other aspects of aeropropulsion system performance, such as cost, acoustic noise, and emissions.

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Presentation Outline

- Background
- Methodology
- Numerical example
- Summary & Concluding Remarks
- Future Works

Objective

- To demonstrate the application of probabilistic approach and its feasibility for aeropropulsion system assessment.

Keys to a Successful Engine Development Program

- Develop reliable and cost-effective technologies.

- Rapid turn around time.

- Make critical decisions in the early stages of engine development - more design freedom and lower cost.

# The Role of Aeropropulsion System Assessment in NASA

• Quantify the benefit of new propulsion technologies.

• Identify the best propulsion system concept amongst several candidates.

• Identify high payoff technologies worthy of pursuit to decision makers.

<u>via conceptual analyses</u>:

- thermodynamic analysis – cycle performance
- flowpath analysis – engine sizing & weight
- mission analysis – fuel burn, emissions
- economic analysis - cost

Why Probabilistic Approach at the Conceptual Stage?
High uncertainty & Relatively low investment

Concept	Design	Production	Product Release
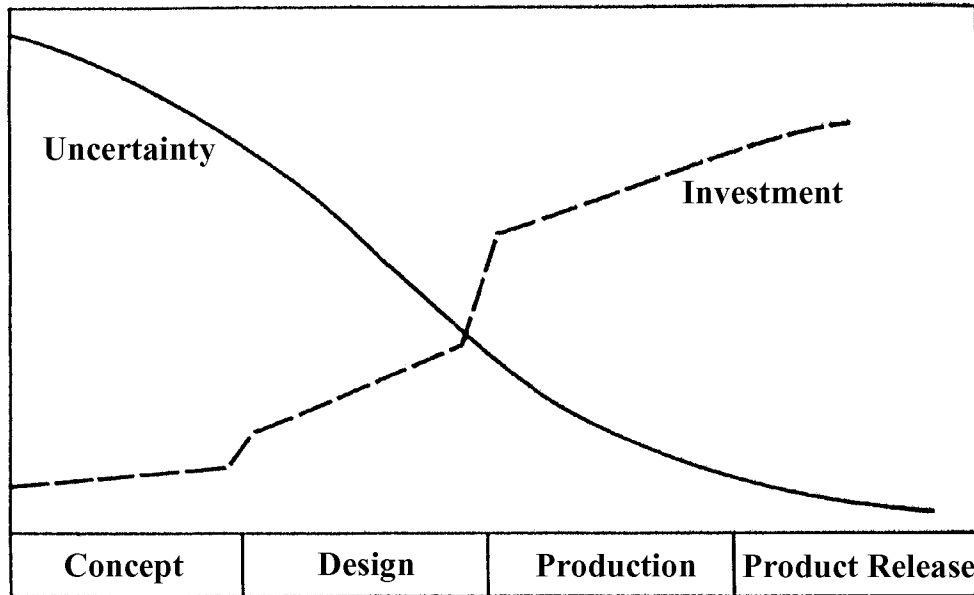
Propulsion System Life Cycle

Aeropropulsion System Design Uncertainties
- Examples

- Uncertainty due to technology infusion.
- Uncertainty in the various engine component performance.
- Uncertainty in mission requirements.
- Uncertainty in cost.
- ……….etc.

Probabilistic Approach
Step-by-Step Procedures

- Identify basic design variables and their uncertainties.

- Quantify the uncertainties with distributions, means, and scatters, based on expert opinion elicitation, historical data, etc.

- Identify the response variables - SFC, thrust, weight, etc.

- Establish functional relationships between the design variables and the response variables
    - analytical expressions, numerical evaluation thru computer codes (such as NEPP*, WATE*).

   *NEPP - NASA Engine Performance Program
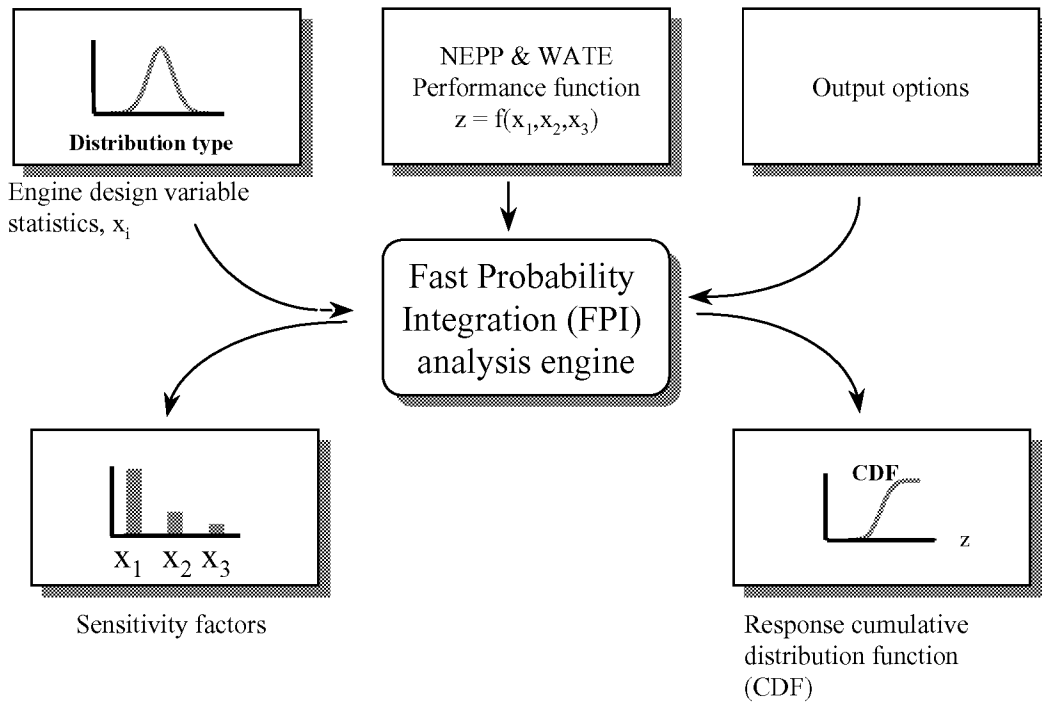   *WATE - Weight Analysis of Turbine Engines

Probabilistic Approach
Step-by-Step Procedures (cont'd)

- Perform perturbation for the selected set of design variables (mean & standard deviation) to generate response variables.
- Perform probabilistic analysis (FORM, SORM, Monte-Carlo, etc.)
    - to compute cumulative distribution functions of the response variables.
    - to compute the sensitivity factors of the response variables.

FORM – First Order Reliability Method
*SORM – Second Order Reliability Method*

Probabilistic Approach - Schematic

Distribution type

Engine design variable
statistics, x_i

NEPP & WATE
Performance function
$z = f(x_1, x_2, x_3)$

Output options

Fast Probability
Integration (FPI)
analysis engine

x_1 x_2 x_3

Sensitivity factors

CDF

z

Response cumulative
distribution function
(CDF)

Numerical Example
A Wave Rotor-Enhanced Turbofan Engine
Sea-Level Static Thrust ≈ 90,000 lbs
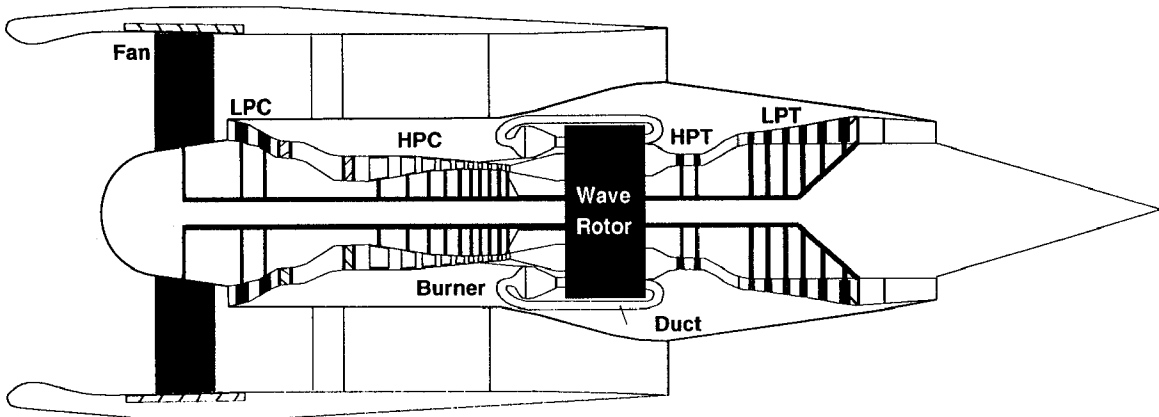
Wave Rotor–Enhanced Turbofan Engine

**Probabilistic assessment of engine SFC, thrust, and weight.**

Design Variables with Uncertainties

| Design Variable	Deterministic Approach (From Ref 1)	Probabilistic Approach		
		Mean	Standard Deviation	Distribution Type
Fan efficiency	0.91	0.91	±0.01	Normal
LPC efficiency	0.88	0.87	±0.01	Normal
HPC efficiency	0.85	0.87	±0.01	Normal
Wave rotor pressure ratio	1.15	1.13	±0.01	Normal
HPT efficiency	0.89	0.88	±0.01	Normal
HPT inlet temp	3200 R	3200 R	±50 R	Normal
LPT efficiency	0.93	0.91	±0.01	Normal
Bleed flow, %	19.5	19.0	±0.5	Normal
Turbine disk material ultimate strength	100 ksi (690 Mpa)	100 ksi (690 Mpa)	±5 ksi (±40 Mpa)	Weibull

Other Design Variables

Design Variable	Deterministic Approach	Probabilistic Approach
Inlet flow	2800 lb/s	
Inlet recovery	1.00	
Inlet temperature	545.7 R	
Fan pressure ratio	1.59	
Fan corrected flow	2875 lb/s	
LPC pressure ratio	1.55	
HPC pressure ratio	15.8	
Wave rotor temp. ratio	1.91	

Probabilistic Approach Quantifies the System Performance Uncertainty
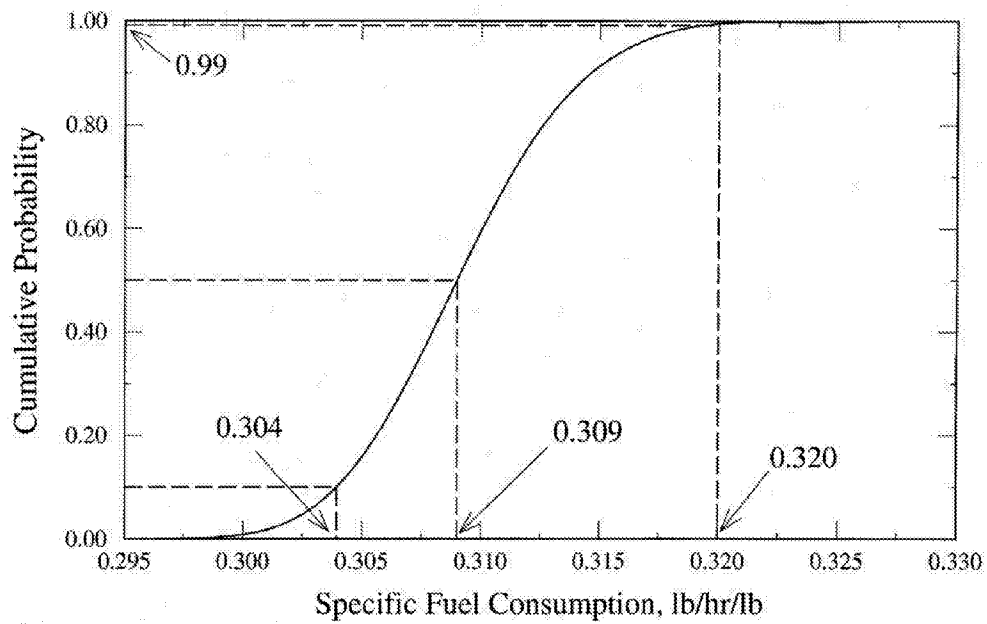
Sensitivity of Specific Fuel Consumption 99% Probability Level

▒ sfc decreases as design variable increases
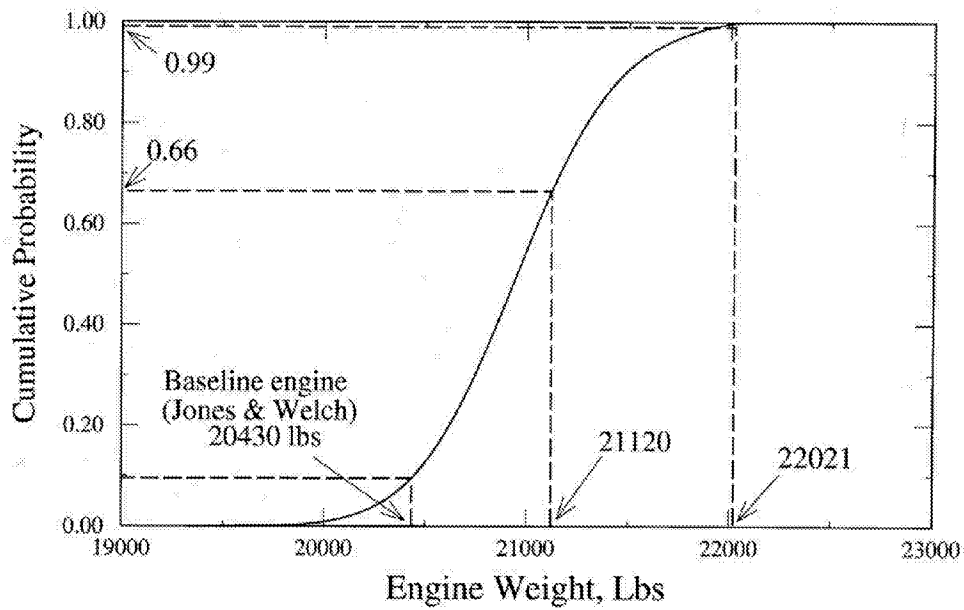▓ sfc increases as design variable increases
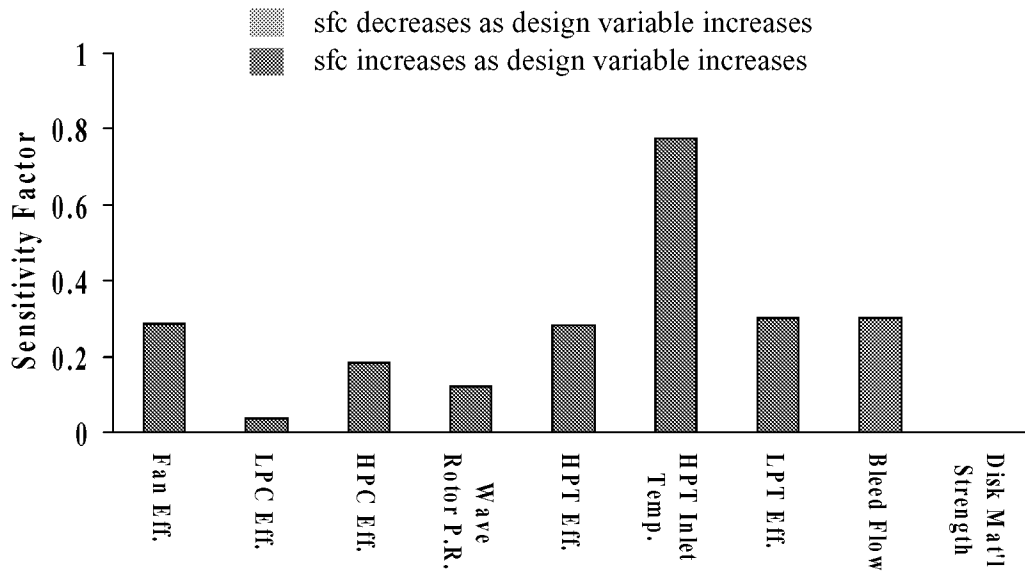
Higher sensitivity factors identify dominant variables to control that would result in biggest payoff.

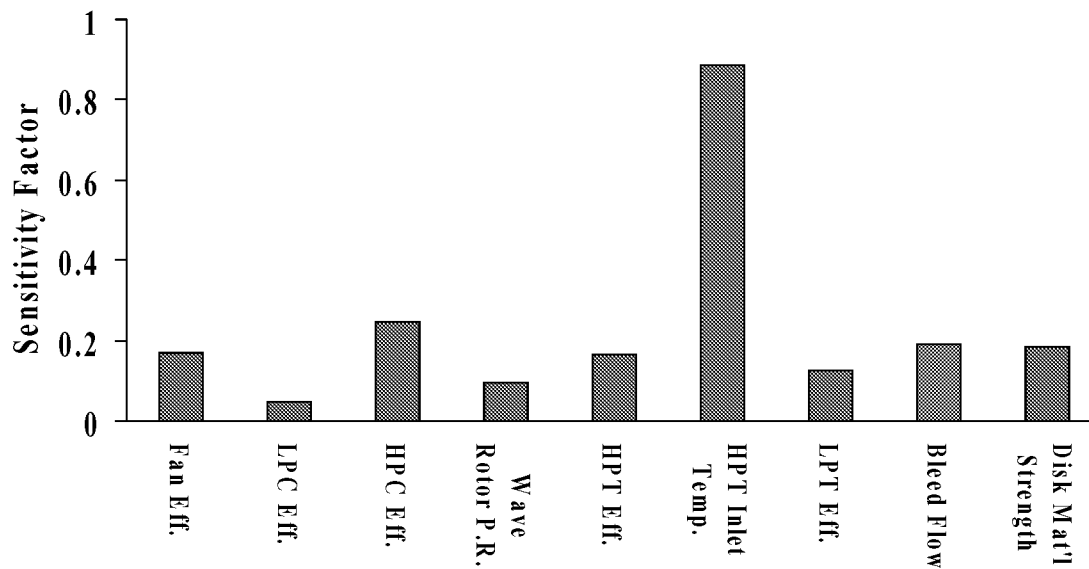# Probabilistic Approach Enables Better Risk Guarantee to the Customers
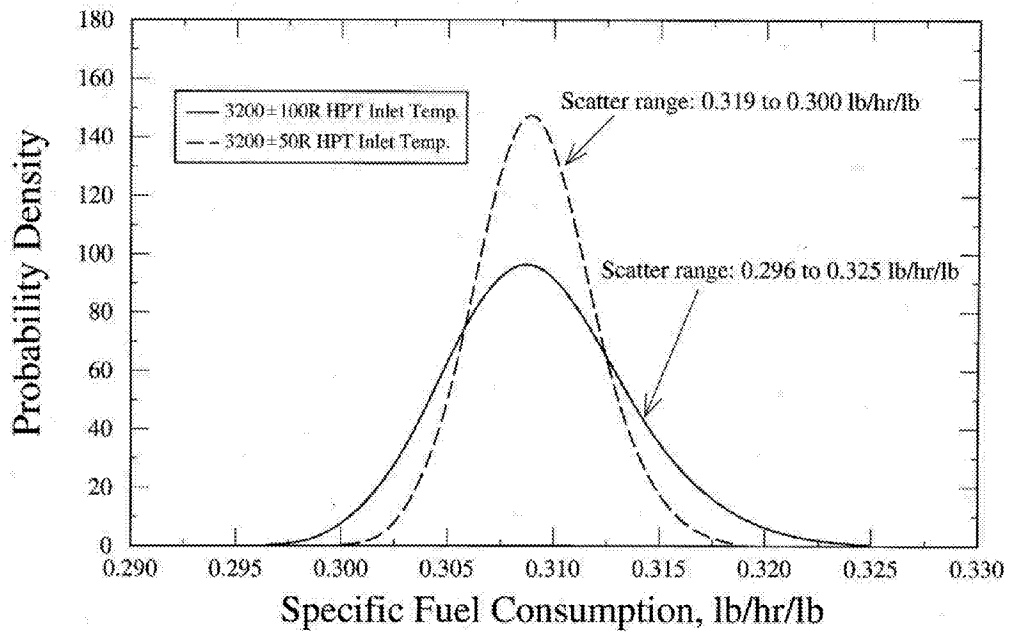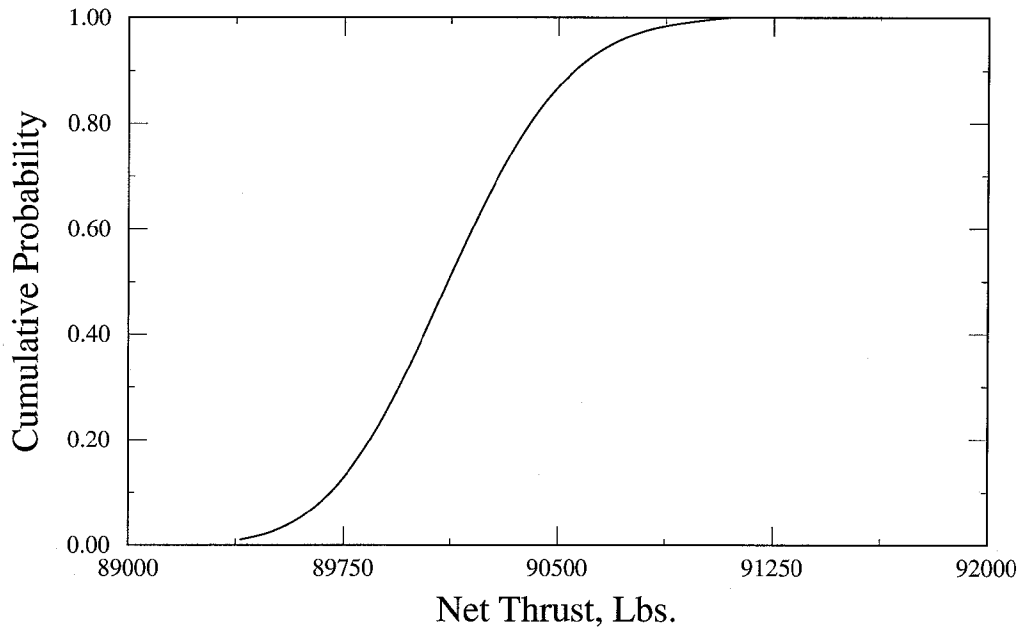

It reduces SFC scatter by about 35%!!!

CDF of Wave Rotor-Enhanced
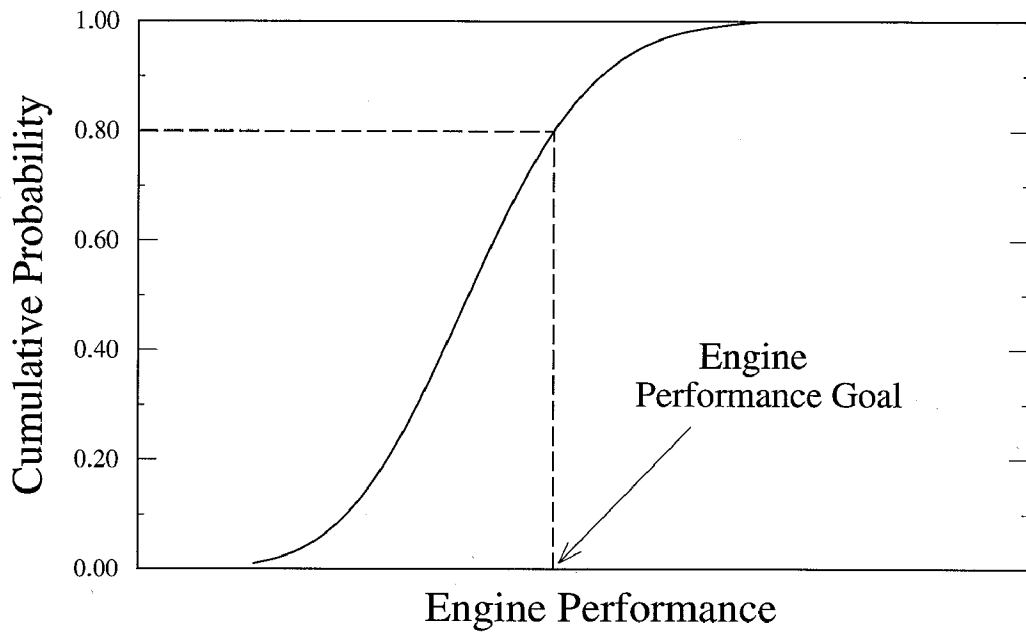# Turbofan Engine Weight

Sensitivity of Engine Weight
99% Probability Level

CDF of Wave Rotor-Enhanced
Turbofan Engine Net Thrust

Probabilistic Approach Enables More Realistic System Assessment

Summary of Probabilistic Approach

• **Quantifies the uncertainties**
  - more realistic and systematic way to develop new
    technologies.

• **Incorporates the 'lessons learned' to quantify the
  development risks**
  - more credible and reliable results.
  - minimize the likelihood of repeating past mistakes.

• **Provides information on risk sensitivity**
  - aid decision-makers in assigning priorities to needed
    technological developments.
  - increase the likelihood that R&D investments will have
    high payoffs.

Summary of Probabilistic Approach (cont'd)

- **Detects problems early before they become critical**
    - development risks can be mitigated early and resources
      (time, funding, manpower, etc.) can be used more wisely.

- **Provides additional insight into the risks associated with new technologies**
    - makes it easier for decision-makers to determine the benefit
      and return-on-investment of a new technology.

Concluding Remarks

- Probabilistic approach is a feasible and rational approach for developing aeropropulsion technologies.

- Effective communication (cooperation) between the technologists and analysts is critical for performing meaningful probabilistic analysis.

The biggest risk of all is ignoring risk!!!

Future Works

- Probabilistic tradeoff analyses –
  - performance – thrust, fuel burn, weight, noise, CO_2 & NO_x emissions
  - durability
  - cost

- Integrate probabilistic system assessment with decision tree analysis to aid decision making

Engine performance, durability, and cost are tradeoffs.