Computational Fluid Dynamics for Simulation Based Design: Challenges and Opportunities

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Outline

- *Why bother?*

- *What are the overarching challenges?*

- *How do we tackle the challenges?*

"It's the affordability, stupid!"

Going forward, we must ensure that the military gets the effective and affordable weapons it needs by redoubling our efforts to enforce procurement discipline.

Leon Panetta, *US Sec. of Def., 2011*

"Designing to affordability, and not just desire or appetite, is critical. Affordability will be incorporated from the start for all new programs."

Robert Gates, *US Sec. of Def., 2010*

"We need to relearn the discipline of affordability…"

Ashton Carter*, US Und. Sec. Def., Acq., Tech. & Log., 2010*

"As we purchase new and modified systems, we will stress reduction of overall life cycle cost—not just the initial acquisition cost."

Paul Kaminski, *US Und. Sec. of Def., Acq. & Tech,* 1995

We can't say we hadn't been warned!

"**In the year 2054, the entire defense budget will purchase just one tactical aircraft… "**

Norm Augustine, LAW NUMBER IX, *Augustine's Laws*, 1983

Tactical Aircraft:

unit cost has increased at a factor of four every ten years since the beginning of the aviation age

Commercial Aircraft:

trend of increasing cost has been basically the same as for military aircraft

Affordability Remains
the Enduring "Grand Challenge" of Flight Vehicles Development for both DoD and Aerospace Industry

(Even More So Today Than Ever)

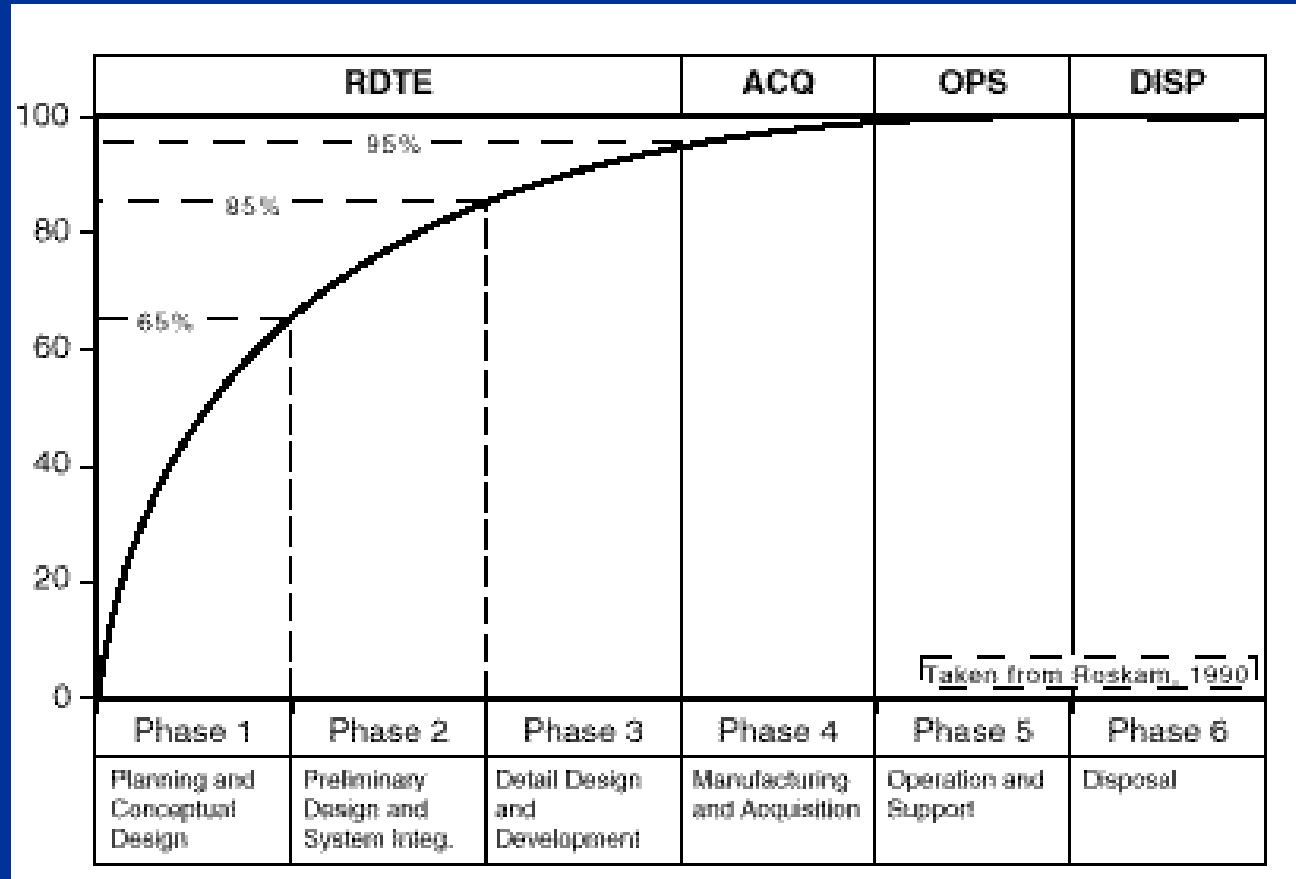# Key to Affordability is Reduced Life Cycle Cost

Components of Life Cycle Cost

Life Cycle Cost (%)

Design & Test	Production	O & S
20	30	50

Ref. 1
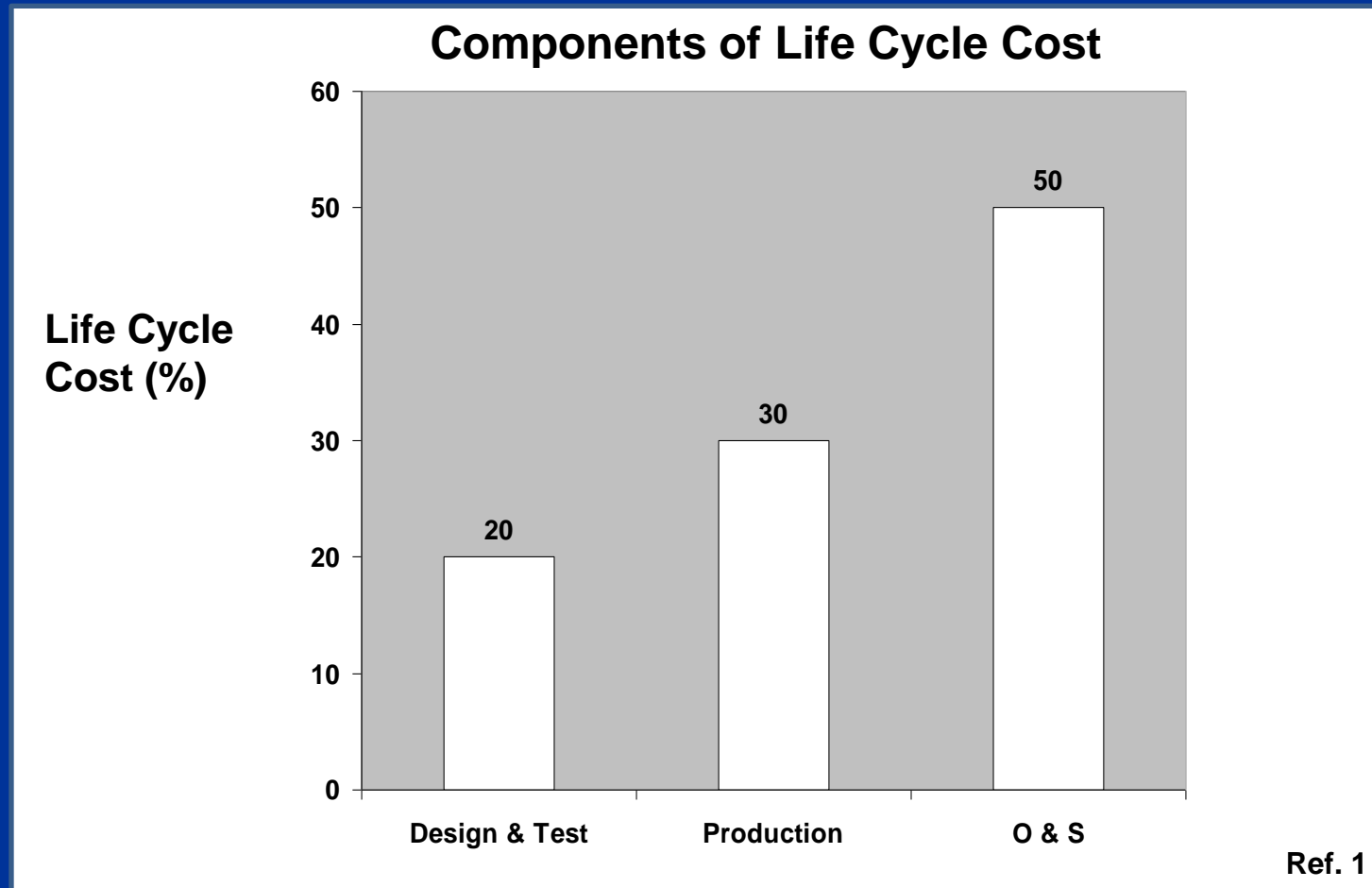
Production + Operation & Support Costs—80% of LCC
Design & Test—only 20%

Early Design Decisions Have Disproportionately Large Impact on LCC

**Program Calendar Time (_Not to Scale_)** ➝

% of LCC Committed

	RDTE			ACQ	OPS	DISP

Chart showing cumulative % of LCC Committed rising steeply through early phases: 65%, 85%, 95% markers. Taken from Roskam, 1990.

Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Planning and Conceptual Design	Preliminary Design and System Integ.	Detail Design and Development	Manufacturing and Acquisition	Operation and Support	Disposal

More Than 80% of LCC is Committed in The Earliest Phases of Design

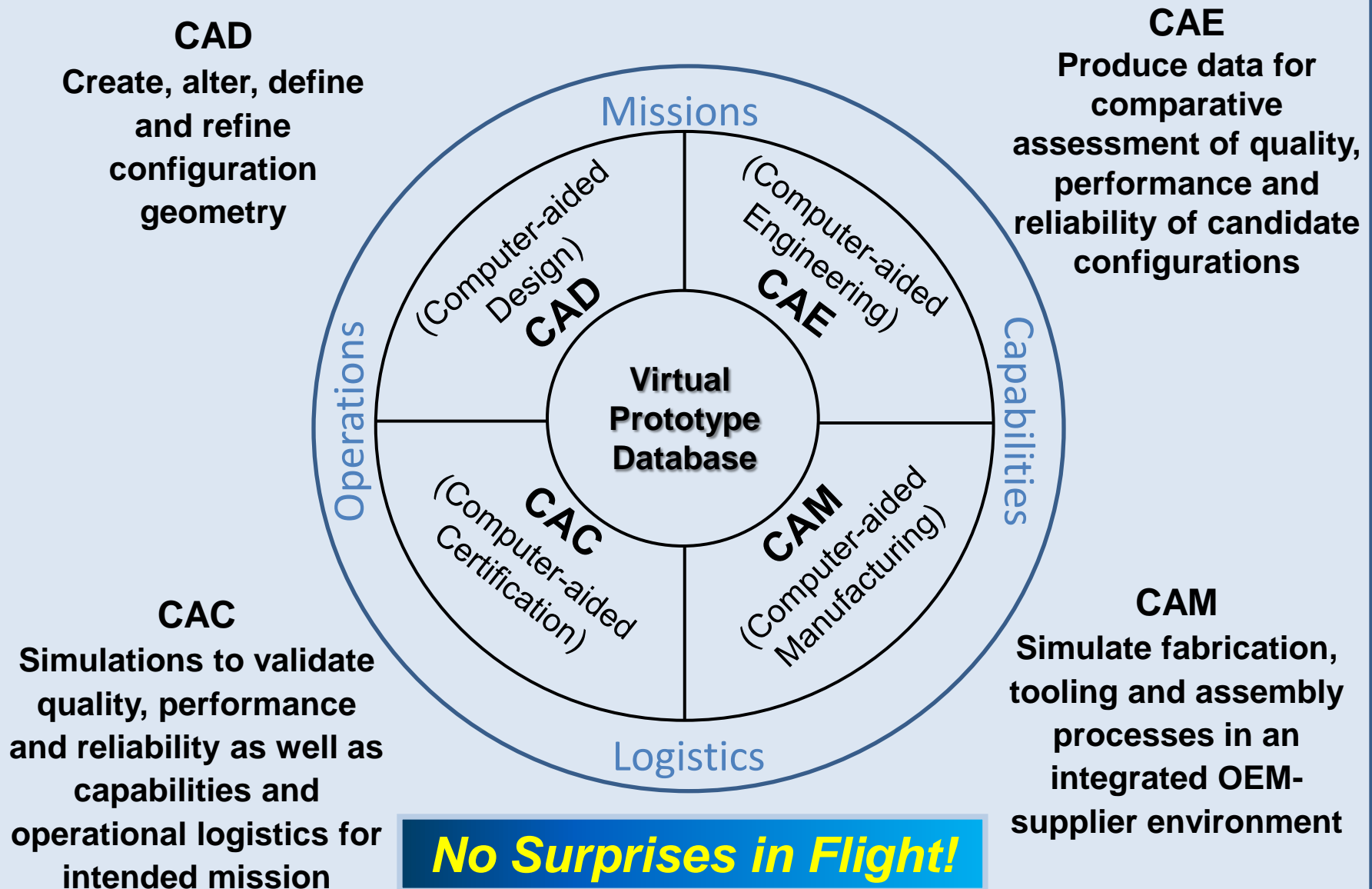# Key to Reducing LCC is Simulation Based Design

Based on Integrated Product & Process Development Concept

- Employs Integrated Multidisciplinary Models and Computational Simulations to develop *Virtual Prototypes*

- Simultaneously Considers All Aspects Including Manufacturing, Operations and Support

- Considers All Requirements and Constraints from Start

- Reduces Need for Design Changes in Later Stages

- Performs Cost/Performance Trade-offs Early--*Using More Knowledge*

- Relies on Computational Methods as the ***primary*** means for all data required to make design decisions
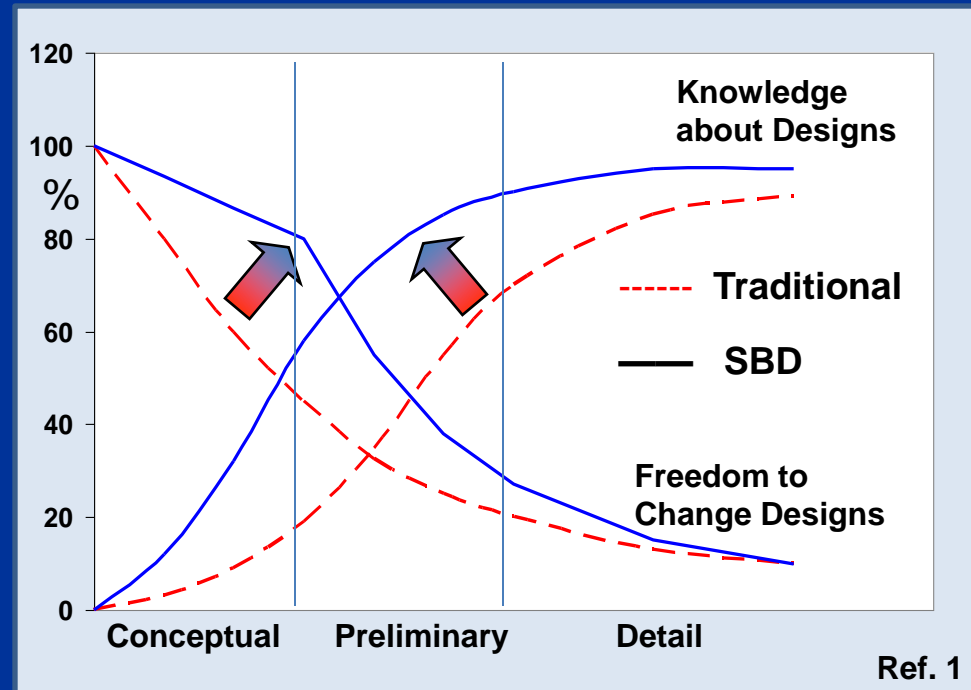
Success Hinges on Availability of Quality Data at the Right Time

SBD is enabled by Integrated Computer-aided Methods

CAD
Create, alter, define and refine configuration geometry

CAE
Produce data for comparative assessment of quality, performance and reliability of candidate configurations

Missions

Operations

Capabilities

Logistics

(Computer-aided Design)
CAD

(Computer-aided Engineering)
CAE

Virtual Prototype Database

CAC
(Computer-aided Certification)

CAM
(Computer-aided Manufacturing)

CAC
Simulations to validate quality, performance and reliability as well as capabilities and operational logistics for intended mission

CAM
Simulate fabrication, tooling and assembly processes in an integrated OEM-supplier environment

No Surprises in Flight!

CFD Plays a Pivotal Role in CAE Simulations for SBD

- **Provides Data for Configuration Design & Evaluation**
  - Product Improvements & Derivatives
    - Evaluation of Design Modifications to Support Integration of New Components and Subsystems
  - New Products
    - Aerodynamic Shape Optimization
    - Multidisciplinary Design Optimization

- **Generates Inputs for Other Disciplinary and Multi-disciplinary Simulations**
  - *Flight Performance Prediction*: Cruise and Maneuver Forces and Moments
  - *Flight Control System Design*: Rate Derivatives
  - *Structural Design*: Steady and Unsteady Flight Loads
  - *Noise Prediction*: Near-field and Far-field Unsteady Flow Fields
  - *Design Optimization*: Sensitivity of Aerodynamic Data to Design Variables
  - ...

CFD is the Linchpin of CAE for SBD

Not All CFD is Equally Effective for Designers!

- **What determines Effectiveness?**

  Effectiveness = Quality x Acceptance

  - *Quality* **Factor**
    - Credible Data (Accurate Prediction of Reality)
  - *Acceptance* **Factors**
    - Timely Results (Fast Data Delivery)
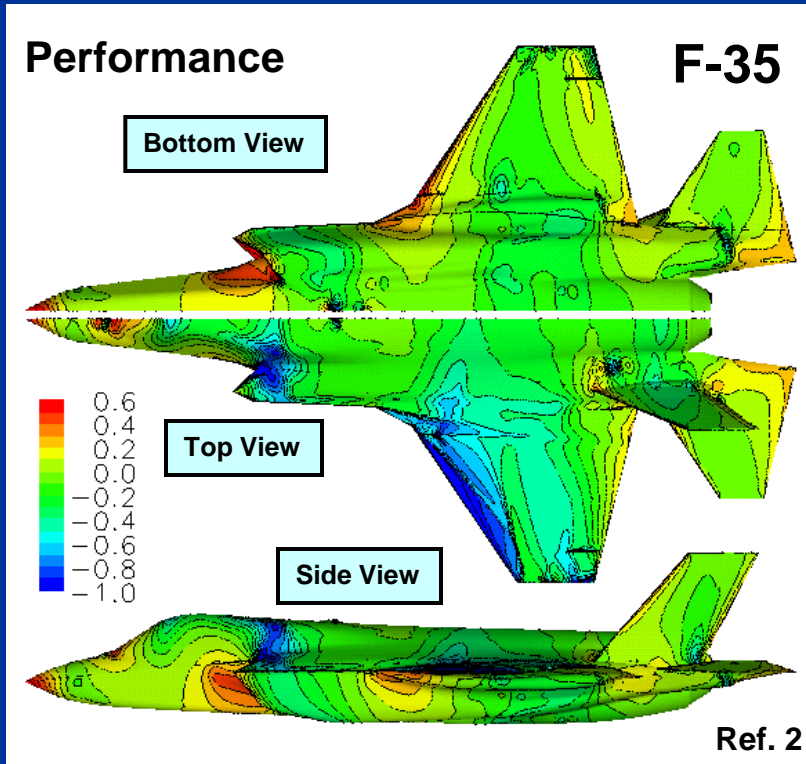   - Low Cost (Low Labor +Computer Expenses)

- **Desired State**
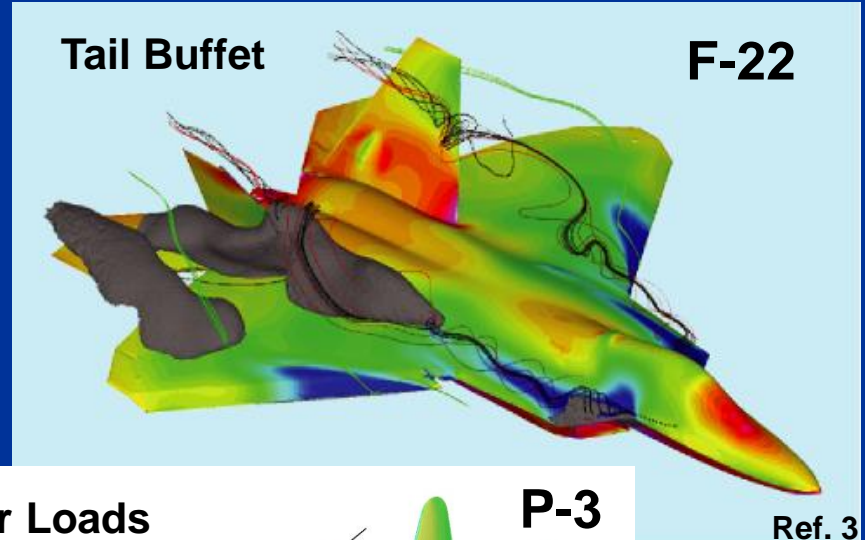 - **Reliable Predictions**
  - **Short Turnaround Time**   *Simultaneously!*
  - **Affordable Cost**

Designers Need/ Want Highly Effective CFD Methods

CFD Today

Performance — F-35
Bottom View
Top View
Side View
Falcon
Ref. 2

Tail Buffet — F-22
Ref. 3
TetrUSS
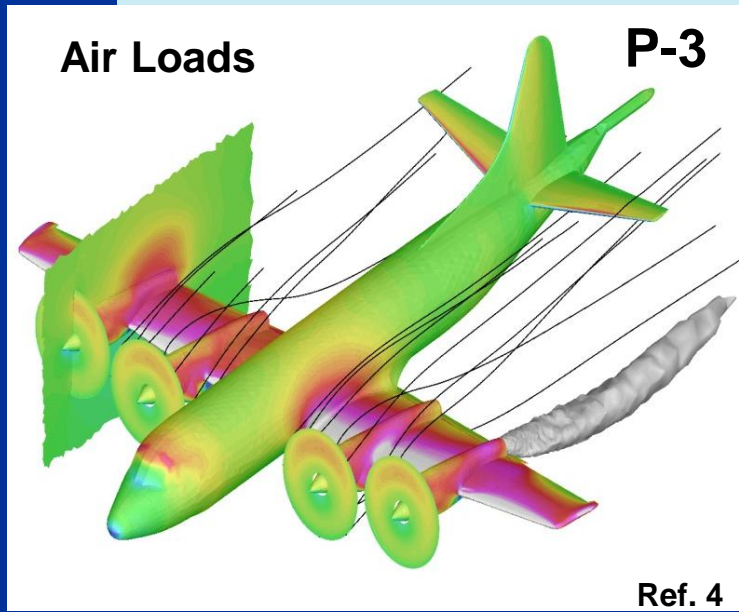
Air Loads — P-3
Ref. 4
TetrUSS

High Fidelity Physics-Based Simulations of Complex Flows About Any Aircraft—Reasonably Fast and Low Cost!

Producing Credible Data Remains the Overarching Challenge for CFD Methods

*How well predictions stack up against reality?

> *What we simulate is not reality itself, but reality determined by our method.*

Why the Credibility Gap?

- **Comprehensive Knowledge and Understanding of *Computational Uncertainty* has been Largely Missing from CFD Applications**

- **Analysts Unable to Provide to Designers *Error Bounds* for Computational Data**

Factors Affecting Data Credibility

- Numerical Models
- Flow Physics Models

Filling the Gap is a Daunting, but Critical, Need

Numerical Models

- **Sensitivity of Results to Variations in Numerical Formulations**
  - **A Representative Example: Effect of Flux-limiter Compression Factors on Surface Pressure in JSF STOVL Analysis**

Angle of Attack = 16°

Ref. 5

Ref. 5
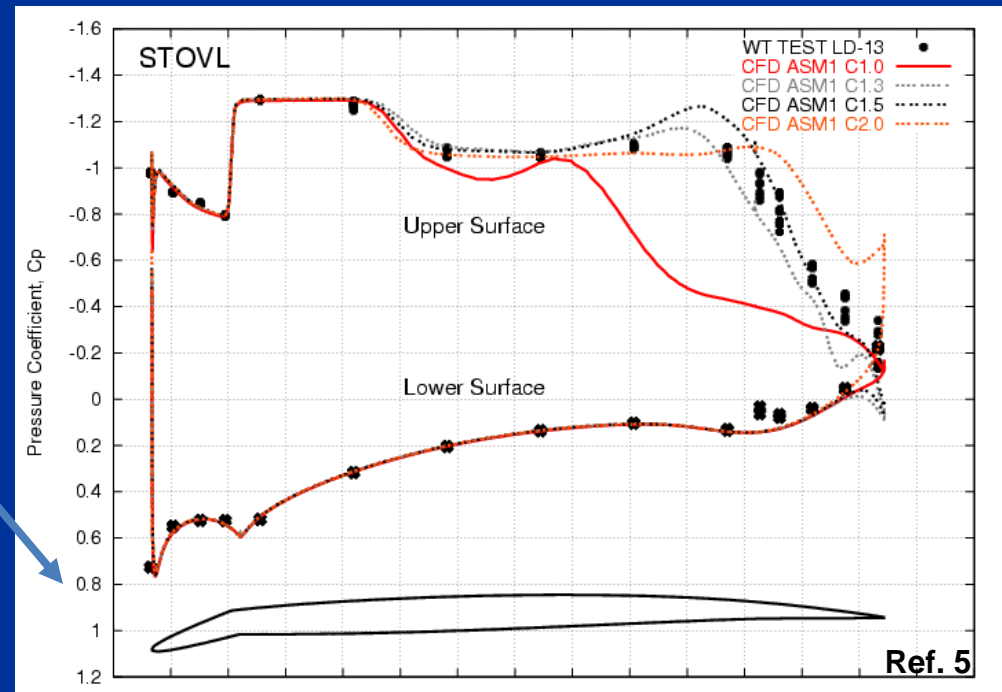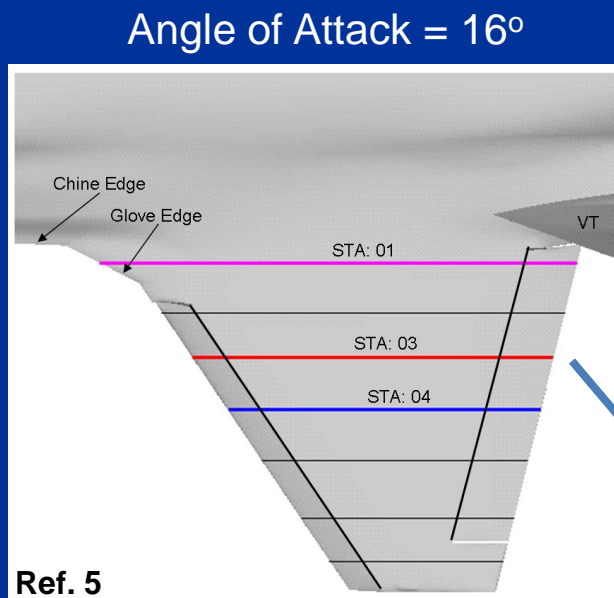
- **Key "Desirements"**
  - **Robust Algorithms--Insensitive to Variations in Numerical Parameters**
  - **Grid-Converged Solutions**
 - **Built-in Means of Quantifying Level of Errors**

Flow Physics Models

- **Traditional "Code Validation" does not increase credibility**

    We cannot validate CFD codes. Period.

    Good results for one application improve chances of credible results for "similar" applications.

- **Reynolds-Averaged Navier-Stokes (RANS) methods suffer from limitations of Transition and Turbulence Models**

VORTICITY MAGNITUDE

K-KL | ASM1 | ASM2

Ref. 5
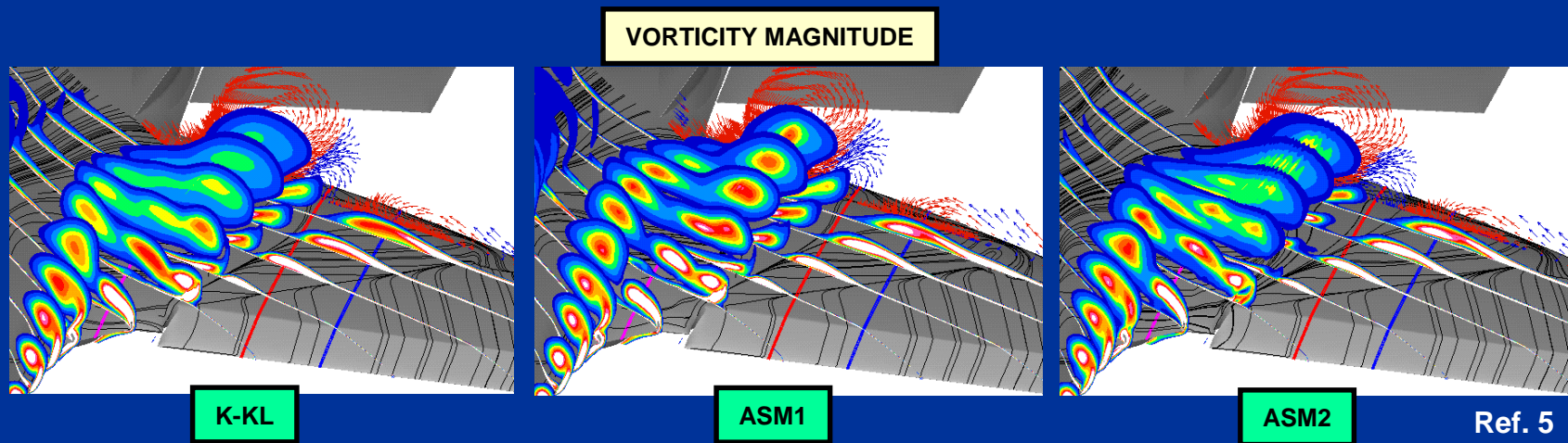
Is turbulence modeling an insurmountable hurdle for accurately simulating complex flows?

"All Models are False, Some are Useful!"

Turbulent Motion of Fluids

"I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic."
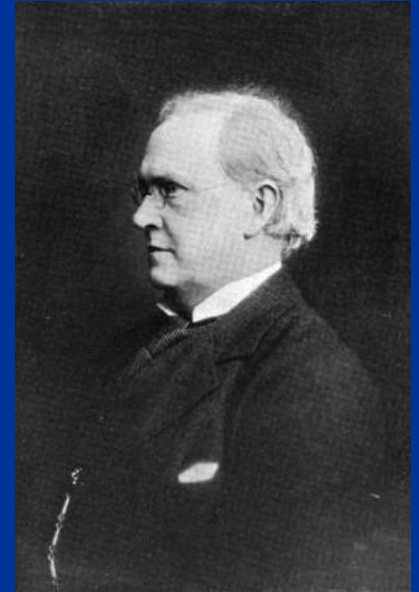
(1849-1934)

Sir Horace Lamb

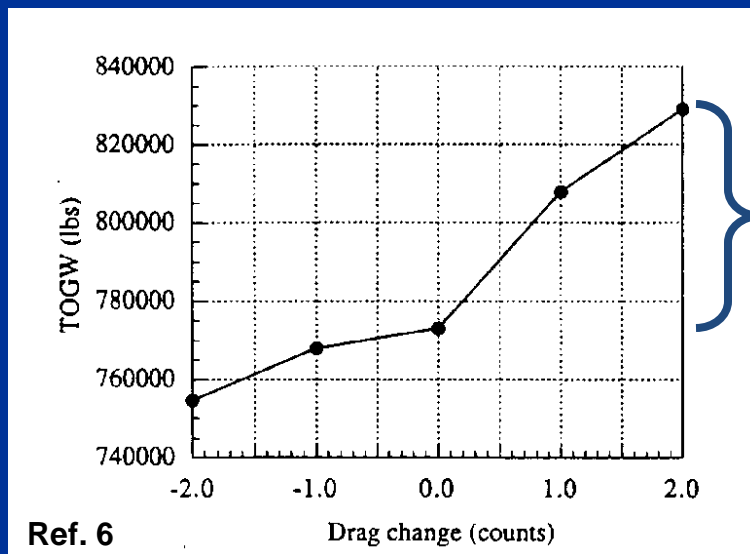*Address to British Assoc. for the Advancement of Science London, U.K., 1932*

We Have Not Heard Back from Sir Lamb--Yet!!!

Image taken from Wikipedia

The Enduring Challenge of CFD

A **Highly Effective** Capability for **Truly Predictive** Flow Simulations

Essential to realizing the full potential benefits of SBD

Ref. 6

Supersonic Transport Aircraft MDO

A two-count "error" in predicting

cruise drag would result in

7% penalty in Take-off Gross Weight !

Suggested approaches to tackle this challenge:

1. **TiCTaC (Tightly Coupled Test and Computations)**

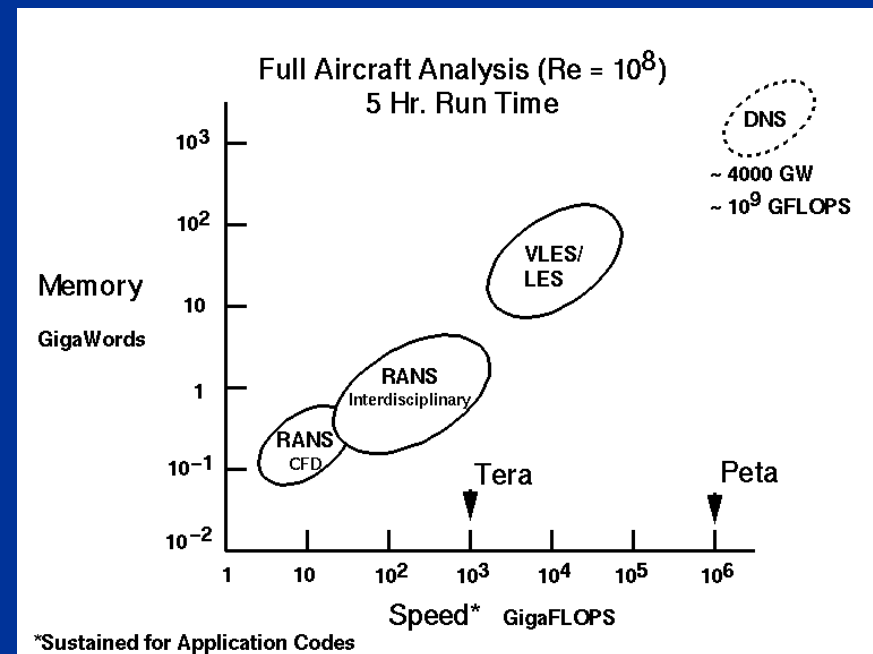2. **DNS (Direct Numerical Simulation)**

TiCTaC
(Tightly Coupled Test and Computations)

- *Premise:* CFD Codes Will NOT Produce Credible Data for *Your Application* Unless Previously Validated on the "Same" Application

- *Approach:* Develop and Implement "Validation Plan" Targeted at Maximizing Prediction Credibility *for Your Application*
  - *Identify the principal source(s) of uncertainty related to modeling of relevant flow physics*
  - *Perform dedicated tests for the sole purpose of "refining" modeling parameters*
  - *Utilize updated models to increase credibility of CFD simulations*

Can We Realize Its Enormous Potential in Practice?

DNS (Direct Numerical Simulation)

- **A straightforward approach that overcomes all RANS deficiencies but unlikely to be practical for a very long time**

  - LES (Large Eddy Simulation) offers a partial solution

- **Progress tied to continued advances in**
  - Computers: Speed, Memory, Cost
  - Algorithms: Robustness & Efficiency
  - Grids: Quality & Automation
  - Software: Productivity & Certification
  - Simulation: Effectiveness
  - Data Management: Storage & Retrieval
  - …

Full Aircraft Analysis (Re = 10^8)
5 Hr. Run Time

DNS
~ 4000 GW
~ 10^9 GFLOPS

VLES/ LES

RANS Interdisciplinary

RANS CFD

Memory GigaWords

10^3

10^2

10

1

10^{-1}

10^{-2}

Tera

Peta

1   10 10^2 10^3 10^4 10^5 10^6

Speed*   GigaFLOPS

*Sustained for Application Codes

A Complete System: Built Around, and Enabled by, HPC. Is it just the Ultimate "Holy Grail?"

Summary

- *"It's the affordability, stupid!"*

- **Reducing Life Cycle Cost (LCC) holds the key to Affordability, and Simulation Based Design (SBD) holds the key to reducing LCC**

  - **SBD is enabled by Integrated Computer-aided Methods (CAD, CAE, CAM, CAC)**

  - **CFD is the Linchpin of Simulations for SBD**

- **A highly effective, truly predictive CFD capability is urgently needed to realize the full potential benefits of SBD for Affordable Weapon Systems**

  - **TiCTaC and DNS offer two avenues**

Thank You!

References

1. Raj, P., "Computational Uncertainty: *Achilles' Heel* of Simulation Based Aircraft Design," NATO/RTO Air Vehicle Technology Symposium on Computational Uncertainty in Military Vehicle Design, Athens, Greece, December 3-6, 2007.
2. Wooden, P.A., and Azevedo, J.J., "Use of CFD in Developing JSF F-35 Outer Mold Lines," *AIAA-2006-3663, 24th Applied Aerodynamics Conference, 2006.*
3. Cunningham, A.M., Jr., Anderson, W.D., Patel, S.R., and Black, C.L., "Lockheed Martin Aeronautics Perspective on Aircraft Buffet Prediction and Analysis," Symposium on Flow-Induced Unsteady Loads and Impact on Military Applications, Applied Vehicle Technology Panel (AVT), NATO, Budapest, Hungary, 25-28 April 2005.
4. Goble, B.D. and Hooker, J.R., "Validation of an Unstructured Grid Euler/ Navier-Stokes Code on a Full Aircraft with Propellers," *AIAA-2001-1003, Aerospace Sciences Meeting, 2001.*
5. Wooden, P.A., Smith, B.R. and Azevedo, J.J., "CFD Predictions of Wing Pressure Distributions on the F-35 at Angles-of-Attack for Transonic Maneuvers," *AIAA-2007-4433, 25th Applied Aerodynamics Conference, 2007.*
6. Giunta, A.A., Golividov, O., Knill, D.L., Grossman, B., Haftka, R.T., Mason, W.H., and Watson, L.T., "Multidisciplinary Design Optimization of Advanced Aircraft Configurations," MAD Center Report 96-06-01, Virginia Tech, Blacksburg, VA.

Flight Vehicles Development Has Become An Ever More Challenging "High Wire" Balancing Act!

Customers Demand Technologically Superior Solutions

    - But Cost Must Not Be Prohibitive

End Users Want Revolutionary Capabilities

    - Quantum Jumps, Not Incremental Improvements

Markets Reward Low Development Risk

    - Risk-Averse Business Environment for An Inherently Risky Business

Buyers Expect On Schedule, On Budget Delivery—Every Time

    - Execute with Competence while Experienced Workforce is Declining

Deliver Quality Systems at Low Cost and Low Program Risk