COMPARING SHIP VERSUS AIRCRAFT DEVELOPMENT COSTS

Larrie D. Ferreiro
Defense Acquisition University

Defense Acquisition University

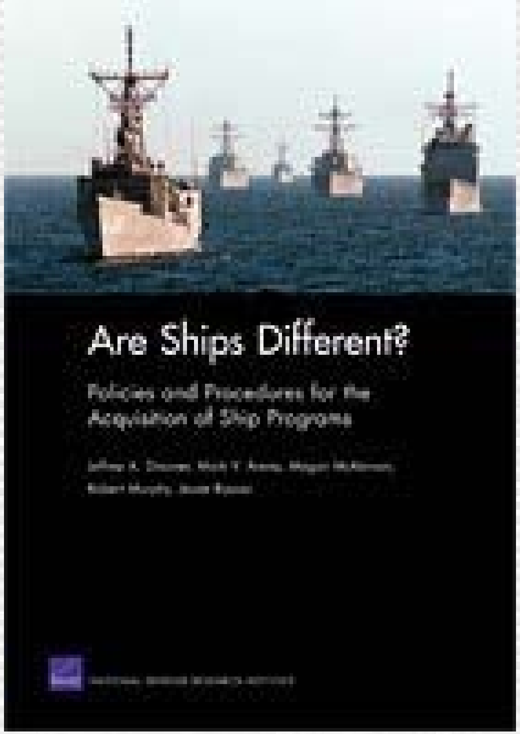
AGENDA

- Introduction and Research Methodology
- Ship versus Aircraft Development Costs in Context
- C-17 versus T-AKE Development Costs
- Analysis of Development Expenditures
- Explanations for Differences in Development Expenditures
- Rationale behind Differences in Development Expenditures
- Conclusions and Recommendations for Further Research

INTRODUCTION AND RESEARCH METHODLOGY

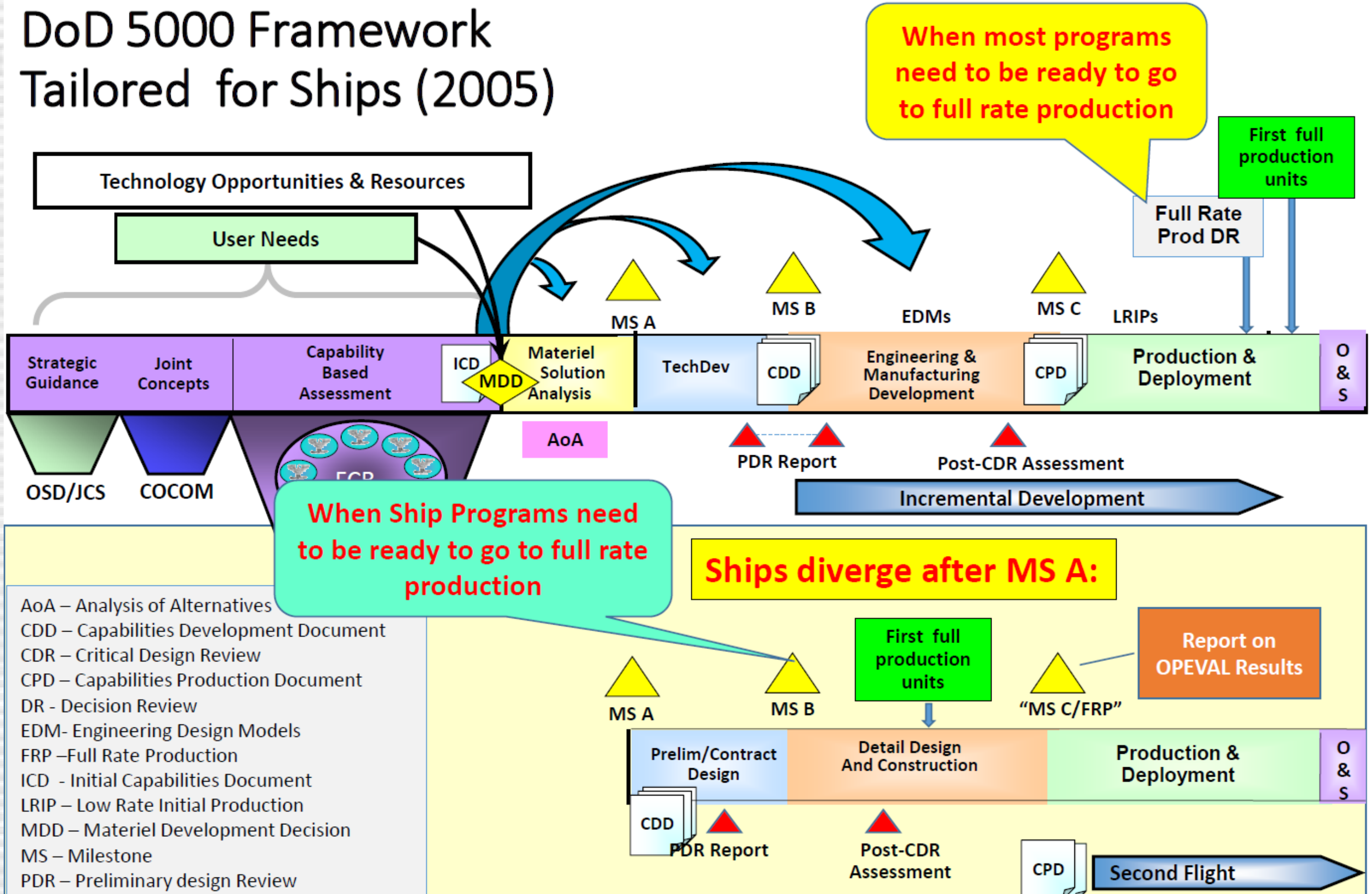
RAND REPORT
ARE SHIPS DIFFERENT?

- "Ship programs do not typically design and build prototype units designated solely for test"
- Full-scale production for ships begins at Milestone B
- Other programs prototyped during engineering development phase after Milestone B
- Full scale production at Milestone C



Spoiler alert: Yes

DoD 5000 Framework Tailored for Ships (2005)



AoA – Analysis of Alternatives
CDD – Capabilities Development Document
CDR – Critical Design Review
CPD – Capabilities Production Document
DR - Decision Review
EDM- Engineering Design Models
FRP –Full Rate Production
ICD - Initial Capabilities Document
LRIP – Low Rate Initial Production
MDD – Materiel Development Decision
MS – Milestone
PDR – Preliminary design Review

DAU

SHIP VERSUS AIRCRAFT DEVELOPMENT COSTS IN CONTEXT

Ship versus Aircraft Costs as of 2005

	UK Type 23 frigate		UK Typhoon fighter	US DDG 51 destroyer		US F22 fighter
Units	16		620	62		187
Development	**$0.7B**	34x	**$24B**	**$ 3B**	10x	**$28B**
Procurement	$4.3B		$23B	$60B		$34B
Total	$5.0B		$47B	$63B		$62B

	T-AKE Cargo ship		C-17 Cargo plane	Cruise Passenger Ship		Airbus A380 Passenger plane
Units	12		190	10		65+
Development	**$0.1B**	50x	**$ 7B**	**$0.06B**	200x	**$13B**
Procurement	$4.6B		$59B	$ 6B		$22B+
Total	$4.7B		$66B	$ 6B		$35B+

Same trend for commercial and military platforms

C-17 VERSUS T-AKE DEVELOPMENT COSTS

C-17 and T-AKE

WHY COMPARE C-17 AND T-AKE?

- Broadly similar missions: carry cargo
- Very few weapon and combat systems
- Cost data available through pubic domain sources

Comparative Development Costs

C-17 (1991)		T-AKE (2001)	
		Early stage designs	1
		Baseline designs	3
		Model basin testing (hull)	1
Structures (fuselage, wing, tail)	221		
Structural analysis	115	Survivability analysis	1
Power system (engines)	119		
Electrical system	26		
Avionics and flight control systems	203		
Mechanical systems (environmental, landing, control surfaces)	95	Environmental, safety and health	1
Mission equipment	11	Mission systems (cargo)	3
Other	11	Other studies	5
Test vehicle manufacturing (1 flyable test aircraft, 2 ground test airframes)	211		
Other unallocated	40		
Systems engineering, design and integration	114	Systems integration design	6
Project management, test & evaluation and support equipment	900	Program management and support	6
		Detailed design	120
Other unspecified, including full-scale testing of 1 flyable test aircraft and 2 ground test airframes	2,130		
TOTAL RDDT (1991)	**4,200**	**TOTAL RDDT (2001)**	**147**
Actual RDDT (2004)	6, 687		

ANALYSIS OF DEVELOPMENT EXPENDITURES

EXAMPLE MAJOR COST ITEMS

C-17	T-AKE
Prototype manufacture + test, 1 flyable craft & 2 ground craft ($2.3B)	Early-stage design work including small-scale model tests ($1M)
Systems integration ($114M)	Systems integration ($6M)
Structural development and analysis ($340M)	Detail design ($120M)
Power and electrical systems ($150M)	
Avionics and flight control, including full-scale cockpit mockups ($200M)	

EXPLANATIONS FOR DIFFERENCES IN DEVELOPMENT EXPENDITURES

SHIP VERSUS AIRCRAFT PROGRAMS

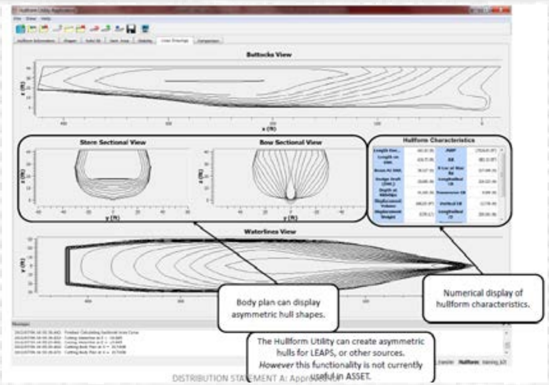
Ship programs generally marked by:

- Competition in design stage only
- Engineering development models at system /subsystem level
- Certification via military specifications, Commercial Vessel Rules or Naval Vessel Rules, modeling and simulation (M&S)

Aircraft programs generally marked by

- Full-scale fly-offs between competing concepts (common for military aircraft like fighters, rare for commercial aircraft)
- Engineering development models at full scale
- Production prototypes at full scale
- Certification via extensive M&S and full scale testing

CONCEPT DEVELOPMENT TO MILESTONE A: SHIPS VERSUS AIRCRAFT



Ships

- Analysis of Alternatives
- Feasibility studies for system reqt's
- Evaluation of system concepts

Aircraft

- Analysis of Alternatives
- Feasibility studies for system reqt's
- Evaluation of system concepts
- Extensive small-scale testing

TECHNOLOGY DEVELOPMENT TO MILESTONE B: SHIPS VERSUS AIRCRAFT

Ships

- Preliminary design
- Small-scale testing
- Some full-scale subsystem prototypes

Aircraft

- Extensive full-scale system prototypes
- One to nine full-scale aircraft prototypes **(i.e., NOT in service)**
- Fly-off

SYSTEMS DEVELOPMENT TO MILESTONE C: SHIPS VERSUS AIRCRAFT

Ships

- Detailed design and construction
- Third-party certification of plans / construction, e.g. ABS
- Test / acceptance of other systems, e.g. radar

Aircraft

- Detailed design and construction
- Numerous full-scale engineering integration models
- Certification by full-scale testing

RATIONALE BEHIND DIFFERENCES IN DEVELOPMENT EXPENDITURES

BOTTOM LINE

Primary driver of the difference between the costs for aircraft and ship development is the *<u>full-scale testing and prototyping for aircraft verification and validation, versus the rules-and-standards-based system for ships</u>*

Why should this be the case?

MYTHBUSTING

1. Myth: Aircraft are inherently more dangerous, so need rigorous full-scale testing of safety-critical systems. Facts: TWA800 lost 230 lives (1996); MV *Estonia* lost 852 lives (1994)
2. Myth: Ships have lower production numbers, so don't warrant prototyping. Facts: DDG 51 has 77 units, F-22 has 187 units, B-2 has 21 units
3. Myth: Aircraft are more complex than ships, so require more extensive testing. Facts: *Ohio* SSBN has 350,000 parts, F-16 fighter has 175,000 parts

- There are NO valid reasons why aircraft could not be designed, tested and built using the rules-and-standards methods for ships, without resort to expensive full-scale prototyping
- Conversely, there are MANY valid reasons why shipbuilding programs could and should incorporate full-scale prototyping as part of the verification and validation process.

So again, why does this difference exist?

Ships are the product of 19th-century rule-of-thumb engineering. The same men who built civil structures like bridges also built ships

Britannia Bridge, 1850

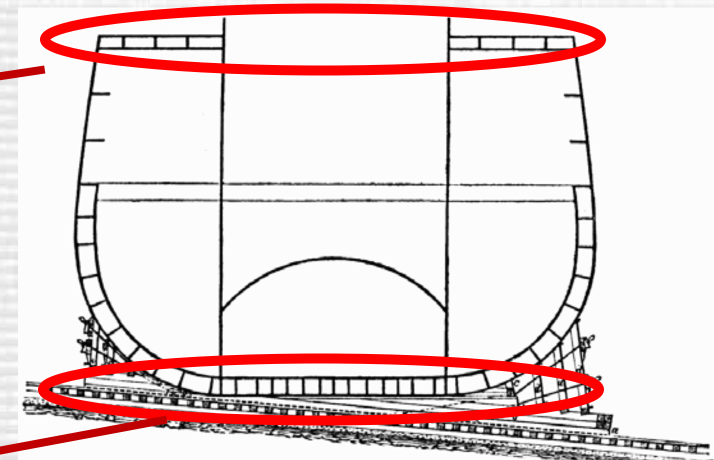


Fig. 15. Transverse Section of Ship, showing Ways and Cradles.

Scale of feet.

***Great Eastern*, 1860**

THE CIVIL ENGINEERING INHERITANCE: "BUILDING CODES" THROUGH THE 20TH CENTURY

STRUCTURAL DESIGN

1607.9.1 General. Subject to the limitations of Sections 1607.9.1.1 through 1607.9.1.4, members for which a value of $K_{LL}A_T$ is 400 square feet (37.16 m²) or more are permitted to be designed for a reduced live load in accordance with the following equation:

$$L = L_o\left(0.25 + \frac{15}{\sqrt{K_{LL}A_T}}\right) \qquad \textbf{(Equation 16-24)}$$

For SI: $L = L_o\left(0.25 + \frac{4.57}{\sqrt{K_{LL}A_T}}\right)$

where:

L = Reduced design live load per square foot (meter) of area supported by the member.

L_o = Unreduced design live load per square foot (meter) of area supported by the member (see Table 1607.1).

K_{LL} = Live load element factor (see Table 1607.9.1).

A_T = Tributary area, in square feet (square meters).

L shall not be less than $0.50L_o$ for members supporting one floor and L shall not be less than $0.40L_o$ for members supporting two or more floors.

TABLE 1607.9.1
LIVE LOAD ELEMENT FACTOR, K_{LL}

ELEMENT	K_{LL}
Interior columns Exterior columns without cantilever slabs	4 4
Edge columns with cantilever slabs	3
Corner columns with cantilever slabs Edge beams without cantilever slabs Interior beams	2 2 2
All other members not identified above including: Edge beams with cantilever slabs Cantilever beams Two-way slabs Members without provisions for continuous shear transfer normal to their span	1

1607.9.1.1 Heavy live loads. Live loads that exceed 100 psf (4.79 kN/m²) shall not be reduced.

Exceptions:

1. The live loads for members supporting two or more floors are permitted to be reduced by a maximum of 20 percent, but the live load shall not be less than L as calculated in Section 1607.9.1.
2. For uses other than storage, where approved, additional live load reductions shall be permitted where shown by the registered design professional that a rational approach has been used and that such reductions are warranted.

1607.9.1.2 Passenger vehicle garages. The live loads shall not be reduced in passenger vehicle garages except the live loads for members supporting two or more floors are permitted to be reduced by a maximum of 20 percent, but the live load shall not be less than L as calculated in Section 1607.9.1.

1607.9.1.3 Special occupancies. Live loads of 100 psf (4.79 kN/m²) or less shall not be reduced in public assembly occupancies.

1607.9.1.4 Special structural elements. Live loads shall not be reduced for one-way slabs except as permitted in Section 1607.9.1.1. Live loads of 100 psf (4.79 kN/m²) or less shall not be reduced for roof members except as specified in Section 1607.11.2.

1607.9.2 Alternate floor live load reduction. As an alternative to Section 1607.9.1, floor live loads are permitted to be reduced in accordance with the following provisions. Such reductions shall apply to slab systems, beams, girders, columns, piers, walls and foundations.

1. A reduction shall not be permitted in Group A occupancies.
2. A reduction shall not be permitted where the live load exceeds 100 psf (4.79 kN/m²) except that the design live load for members supporting two or more floors is permitted to be reduced by 20 percent.
3. A reduction shall not be permitted in passenger vehicle parking garages except that the live loads for members supporting two or more floors are permitted to be reduced by a maximum of 20 percent.
4. For live loads not exceeding 100 psf (4.79 kN/m²), the design live load for any structural member supporting 150 square feet (13.94 m²) or more is permitted to be reduced in accordance with the following equation:

$$R = 0.08\,(A - 150) \qquad \textbf{(Equation 16-25)}$$

For SI: $R = 0.861\,(A - 13.94)$

Such reduction shall not exceed the smallest of:

1. 40 percent for horizontal members;
2. 60 percent for vertical members; or
3. R as determined by the following equation.

$$R = 23.1\,(1 + D/L_o) \qquad \textbf{(Equation 16-26)}$$

where:

A = Area of floor supported by the member, square feet (m²).

D = Dead load per square foot (m²) of area supported.

L_o = Unreduced live load per square foot (m²) of area supported.

R = Reduction in percent.

NYC Structural Design Code

15.3.7 ***Sheerstrake Thickness***

In general, the thickness of the sheerstrake is to be not less than the thickness of the deck stringer plate, nor is it to be less than the thickness of the side-shell plating. The thickness of the sheerstrake is to be increased 25% in way of breaks of superstructures, but this increase need not exceed 6.5 mm (0.25 in.). Where the breaks of the forecastle or poop are appreciably beyond the midship 0.5L, this requirement may be modified.

15.3.8 ***Bottom Shell Plating Amidships***

a ***Extent of Bottom Plating Amidships*** The term "bottom plating" refers to the plating from the keel to the upper turn of the bilge for 0.4L amidships.

b ***Bottom Shell Plating*** The thickness of the bottom shell plating for the midship 0.4L is not to be less than that obtained from the following equations.

1 *For Vessels with Transversely-framed Bottoms and not exceeding 228 meters (750 feet) in Length*

$$t = \frac{s}{519}\sqrt{(L-19.8)(d/D_s)} + 2.5 \text{ mm}$$

$$t = \frac{s}{940}\sqrt{(L-65)(d/D_s)} + 0.1 \text{ inches}$$

2 *For Vessels with Longitudinally-framed Bottoms*

Vessels less than 122 meters (400 feet) in length

$$t = \frac{s}{671}\sqrt{(L-18.3)(d/D_s)} + 2.5 \text{ mm}$$

$$t = \frac{s}{1215}\sqrt{(L-60)(d/D_s)} + 0.1 \text{ inches}$$

Vessels of 122 meters (400 feet) or more but not exceeding 305 meters (1000 feet) in length

$$t = \frac{s}{508}\sqrt{(L-62.5)(d/D_s)} + 2.5 \text{ mm}$$

$$t = \frac{s}{920}\sqrt{(L-205)(d/D_s)} + 0.1 \text{ inches}$$

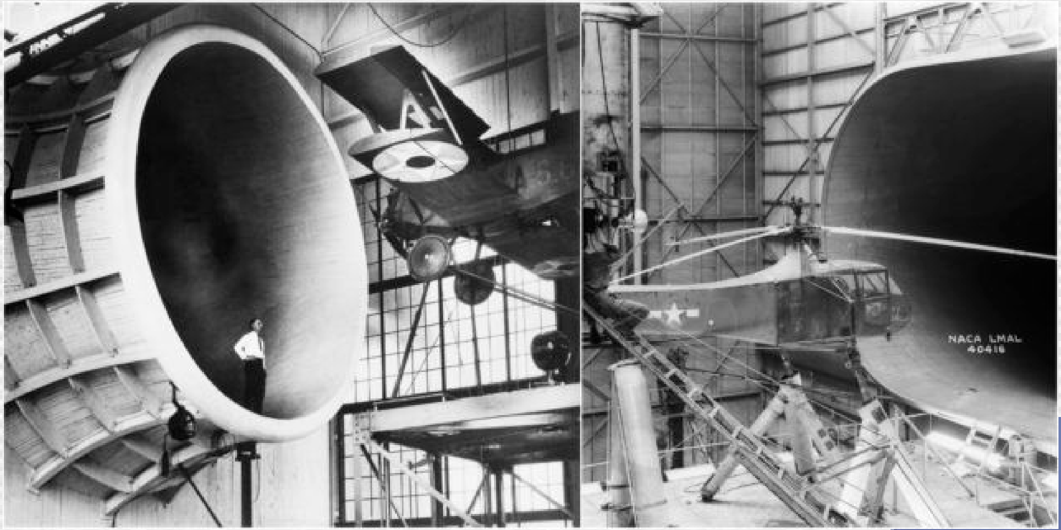
where L, d, D_s are in meters or in feet, s is in millimeters or in inches as defined in 15.3.5.
The d/D_s ratio is not to be taken less than 0.65.

c ***Plate Keels*** For plate keels see 4.1.

15.3.9 ***Minimum Thickness***

After all necessary corrections have been made, the thickness of shell plating amidships below the upper turn of bilge for ships of unrestricted

ABS Steel Vessel Rules



Aircraft are the product of 20th century physics-based engineering. Prandtl and von Karman had the same education as Einstein

In the 1920s, the USN funded 2 ship model basins, EMB and Michigan
Same time, NACA had 12 wind tunnels
EMB had $100K annual funding
NACA had $1.3M annual funding

AIRCRAFT ONCE HAD THE SAME CLASSIFICATION PROCESS AS SHIPS

- In the 1930s, Aircraft International Register (AIR) set up to provide classification services for aircraft as they did with ships
- ABS, LR, BV all set up aircraft divisions
- Governments took over airworthiness certification, AIR folded in 1939

CONCLUSIONS

- Aircraft cost 10-200x more to develop than ships
- This is due to extensive use of full-scale prototyping in the aircraft industry, never done for ships. This is NOT because of any inherent technical differences between platforms
- Reason is that ships are product of 19th century rule-of-thumb engineering, aircraft product of 20th century physics-based engineering
- Even in the 21st century, engineering culture is more difficult to change than technology

RECOMMENDATIONS FOR FURTHER RESEARCH

- Investigate cost-benefit of full-scale prototyping as part of shipbuilding verification and validation
- Initial investment versus savings in lives / property / availability, e.g., from reduced damage from collisions
- US Navy can lead the way as it has done in past

QUESTIONS?