Airplane Design Issues with Formation Flying

Massachusetts Institute of Technology

16.899 Air Transportation Systems Architecting

Bob Liebeck

March 11, 2004

BOEING PHANTOM WORKS ™

Cargo Vehicle Designs

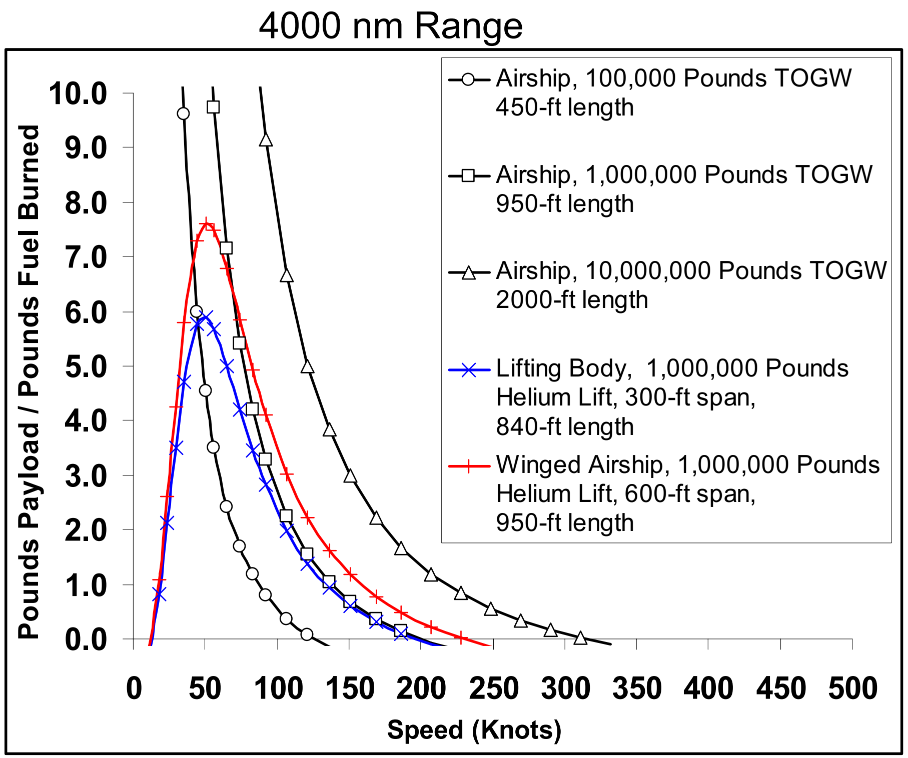
- Ships
  - very large displacement ships
  - semi-planing ships, fast catamarans
  - hydrofoils
- Airships
  - pure displacement
  - lifting body
  - hybrid (wing-body)
- Conventional Airplanes
- Modular/Convertible Airplanes
- Formation Flying

  - multiple airplanes in formation with one another

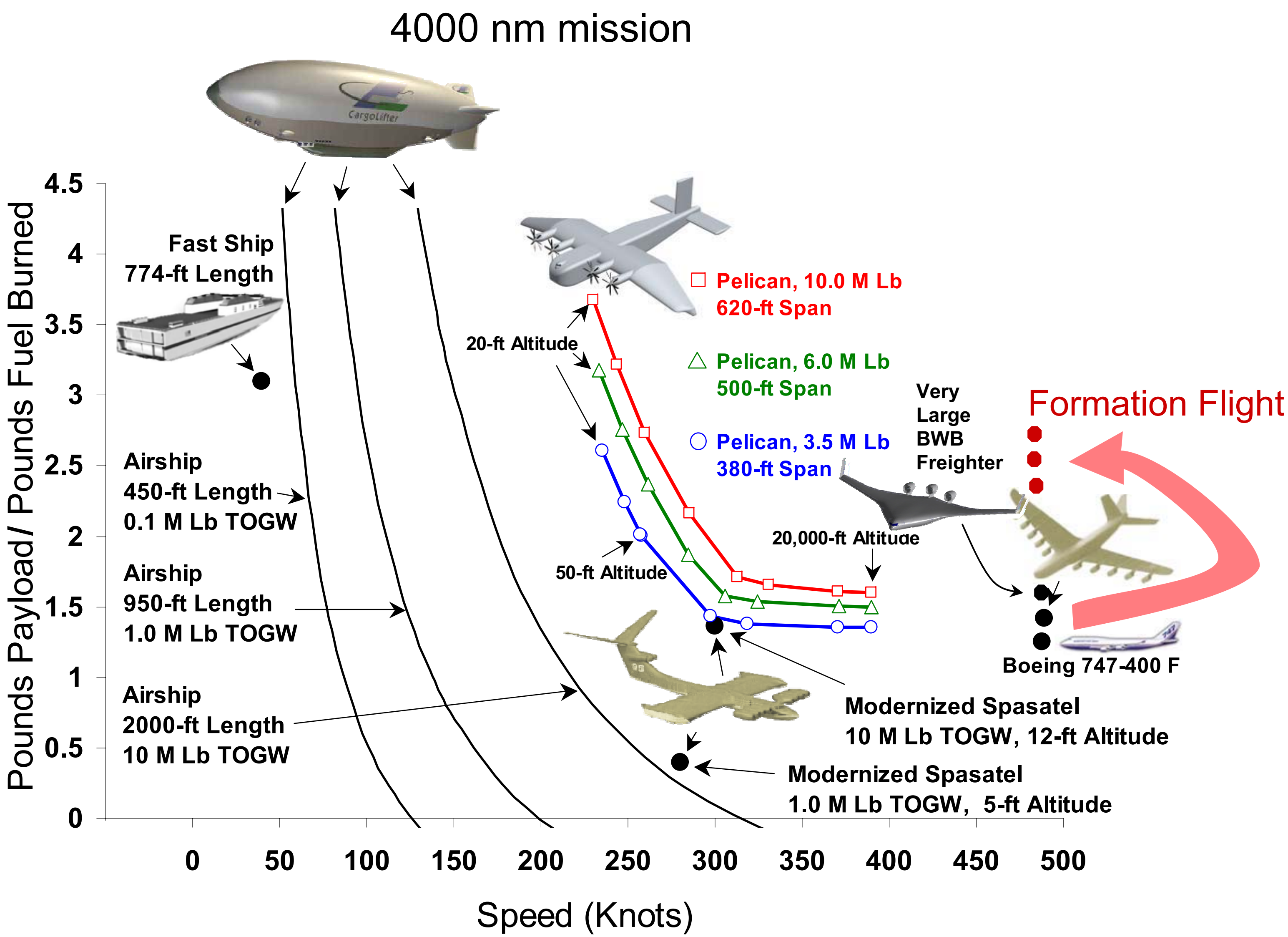
  - wing-in-ground-effect (airplane in formation with itself)

Airships

- Airship performance increases with size
  - Fast and efficient airships are big
- Lifting body or wing-body airships can provide improved operational characteristics
  - Variation in load, altitude
  - Improved cargo handling
  - But:
    - No hover at higher weights
    - Little change in cruise performance



Comparison of Freighters



Existing Conventional Freighters

747-400F

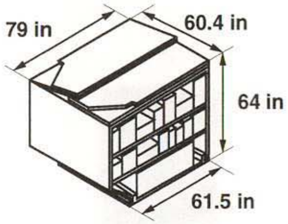
MD-11F

All Derivatives of Commercial Airliners

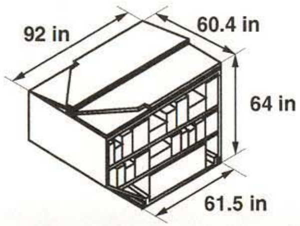
Super Transporter

747 Lower Hold Capability

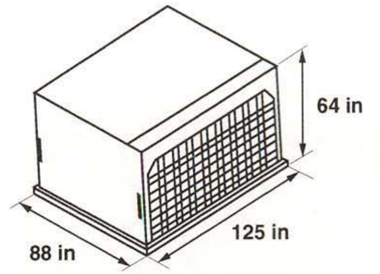
Basic



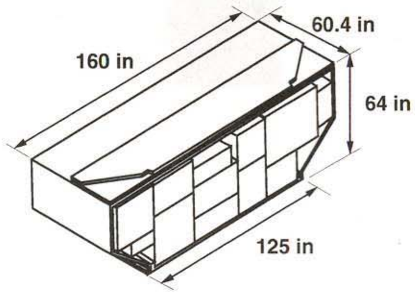
3,500 lb (1,588 kg) **MGW**
159 ft^3 (4.5 m^3)
(LD-3)



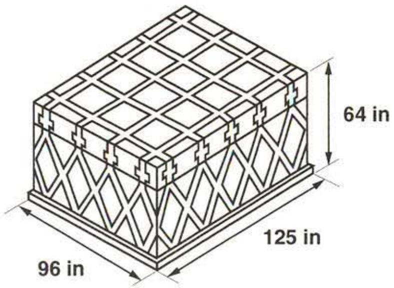
3,500 lb (1,588 kg) **MGW**
175 ft^3 (4.9 m^3)
(LD-1)



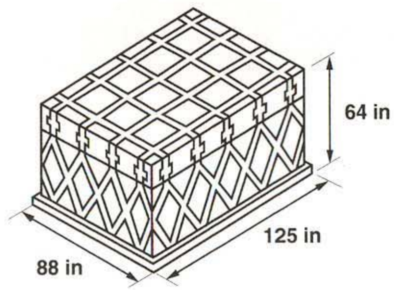
10,200 lb (4,627 kg) **MGW***
381 ft^3 (10.8 m^3)
(LD-9)



7,000 lb (3,175 kg) **MGW***
322 ft^3 (9.1 m^3)
(LD-6)



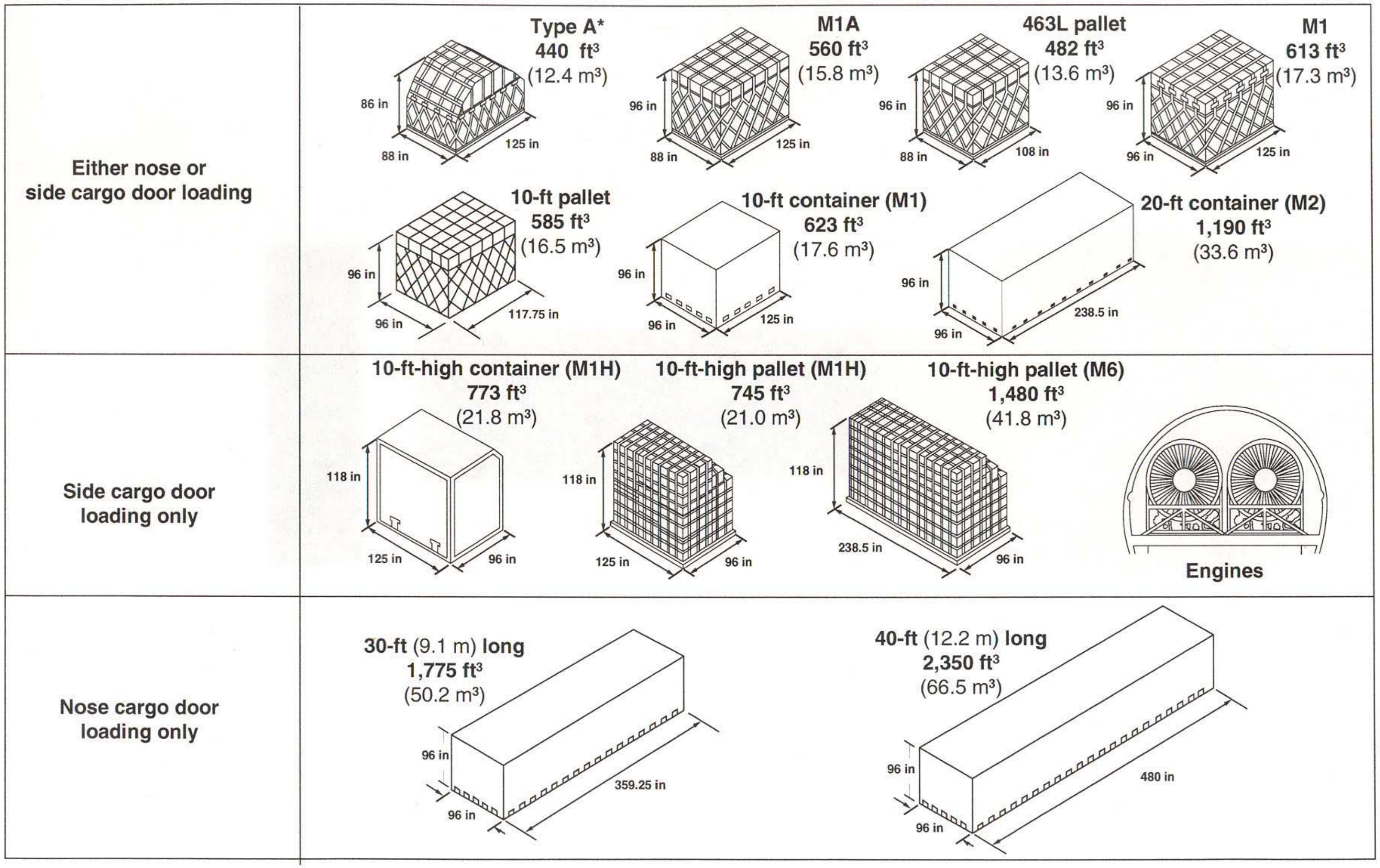
11,100 lb (5,035 kg) **MGW***
415 ft^3 (11.8 m^3)



10,200 lb (4,627 kg) **MGW***
372 ft^3 (10.5 m^3)

* Maximum gross weights (MGW) shown are based on lower hold running load capability (116 lb/in), subject to overall airframe structural limits

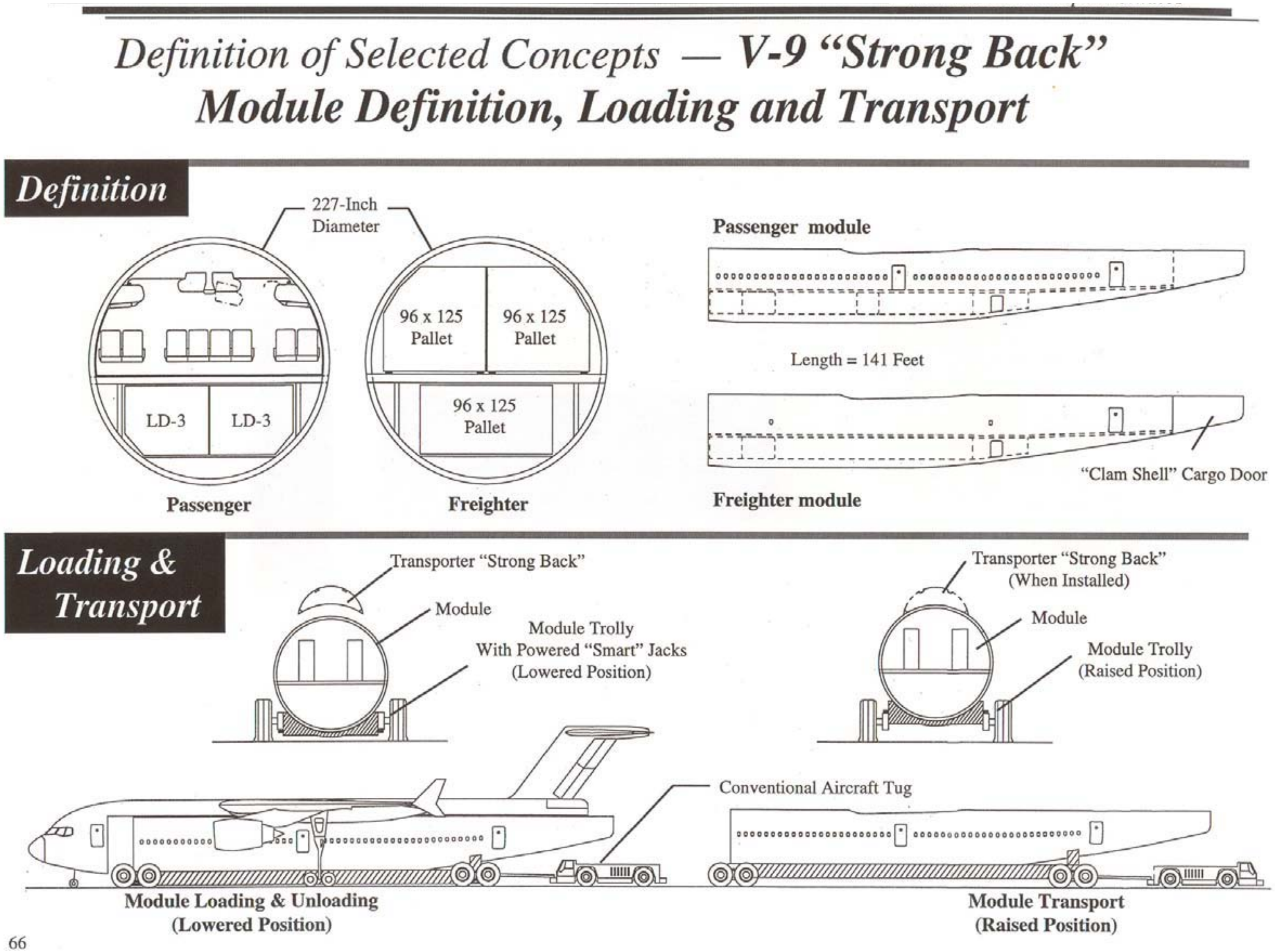
747 Main Deck Capability



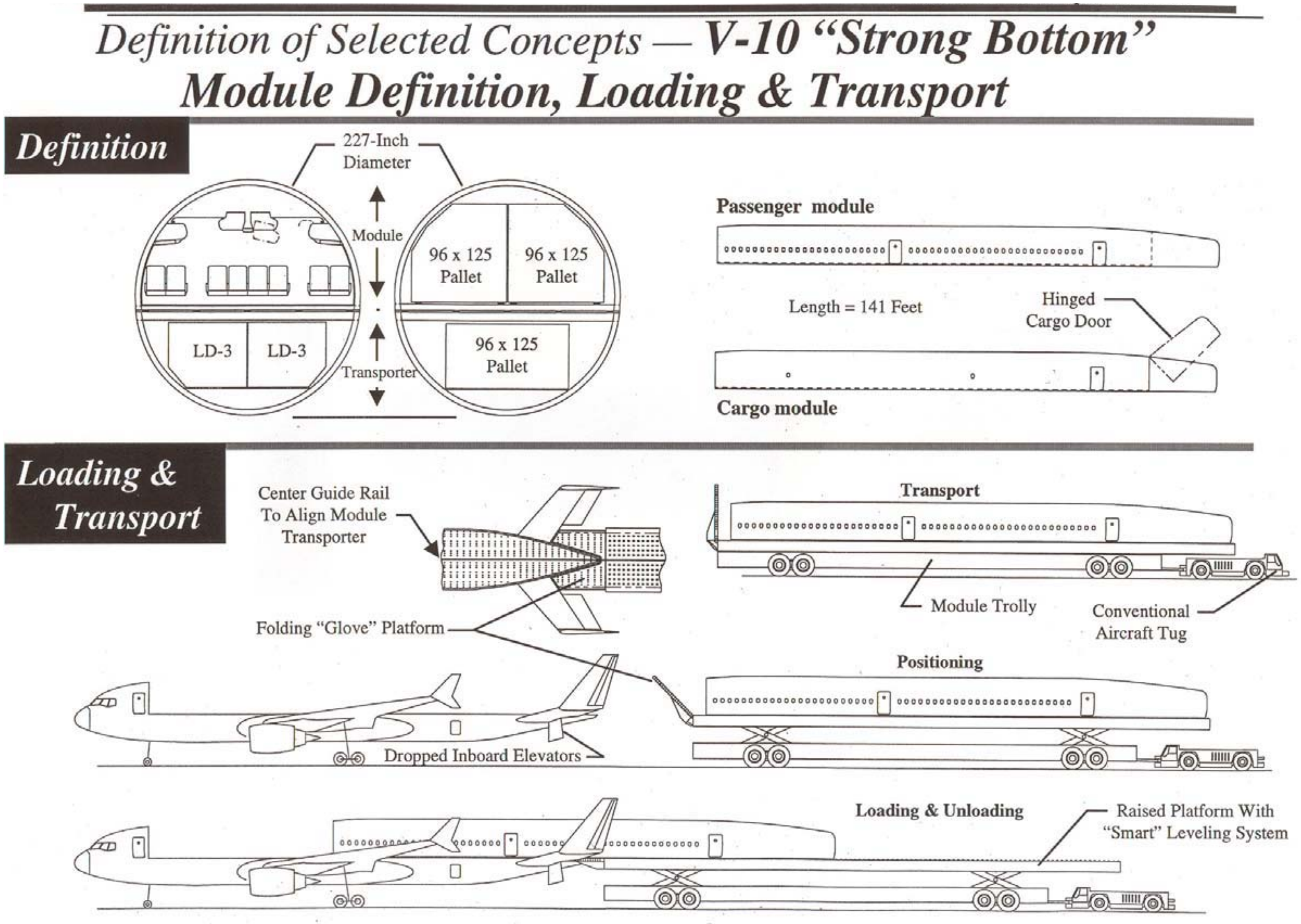
Volumes are based on SAE Aerospace Standard, AS 1825

* Maximum height varies from 78 to 86 in (198 to 218 m), depending on airplane type (e.g., 707, 727, 757, DC-8)

Intermodal Transport Studies

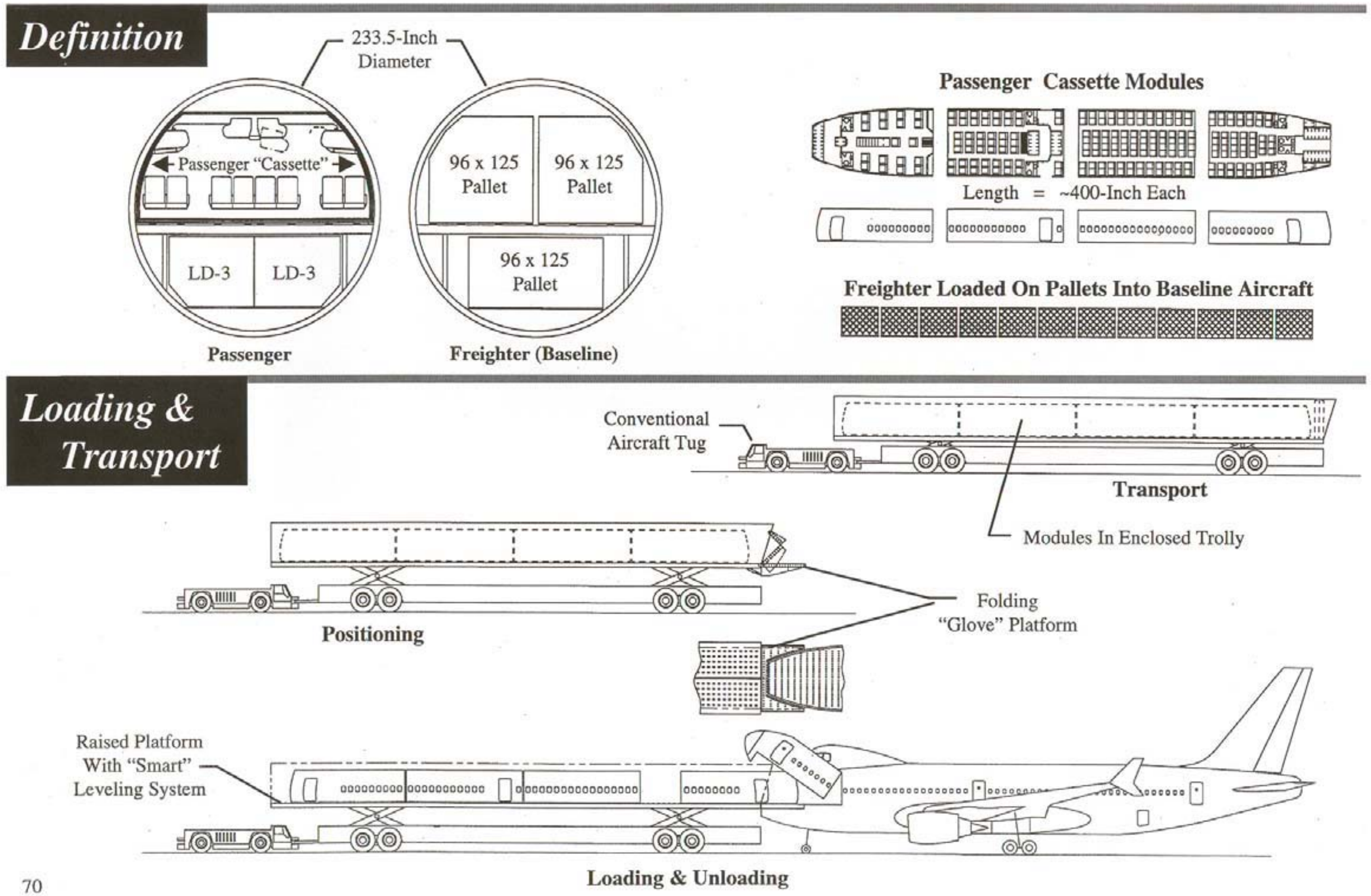


Intermodal Transport Studies



Intermodal Transport Studies

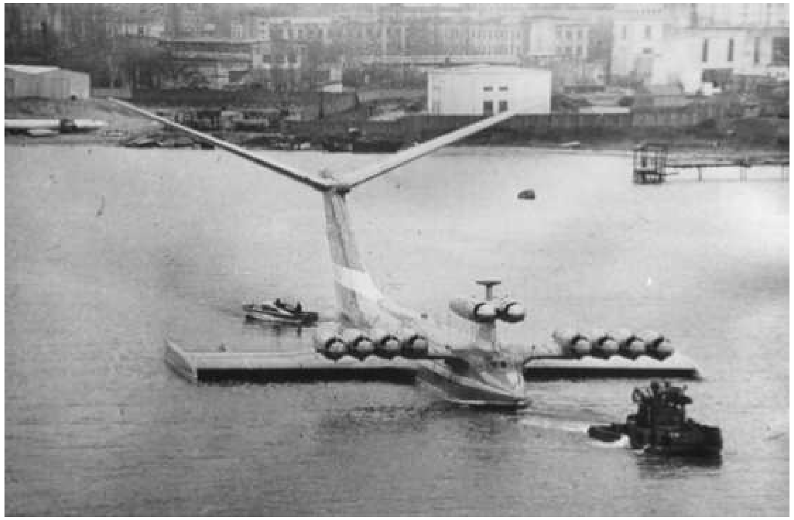
Definition of Selected Concepts —
V-11 "Cassette" Module Definition, Loading & Transport

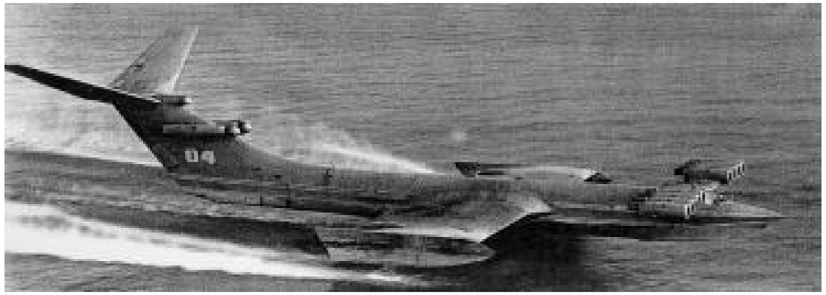


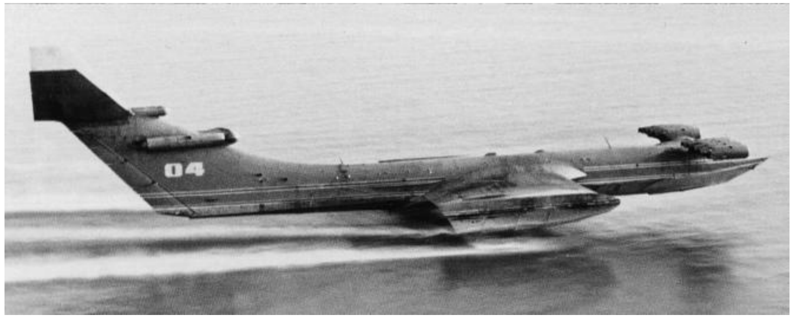
JSC R.E. Alexeiev Central Hydrofoil Design Bureau
"KM"

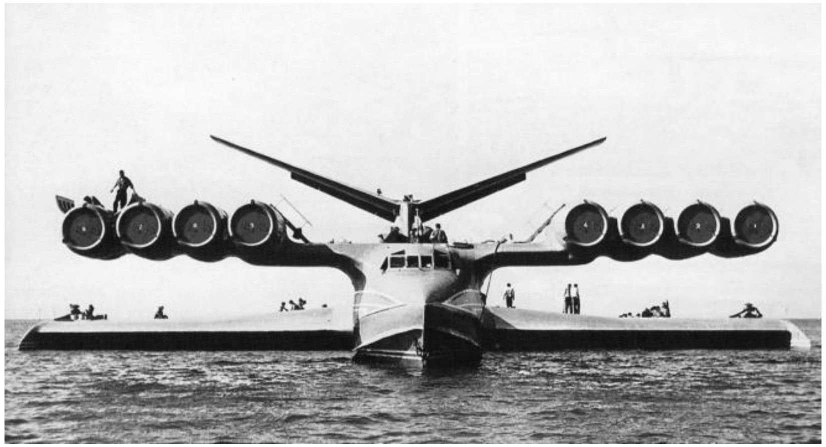
JSC R.E. Alexeiev Central Hydrofoil Design Bureau

"KM"



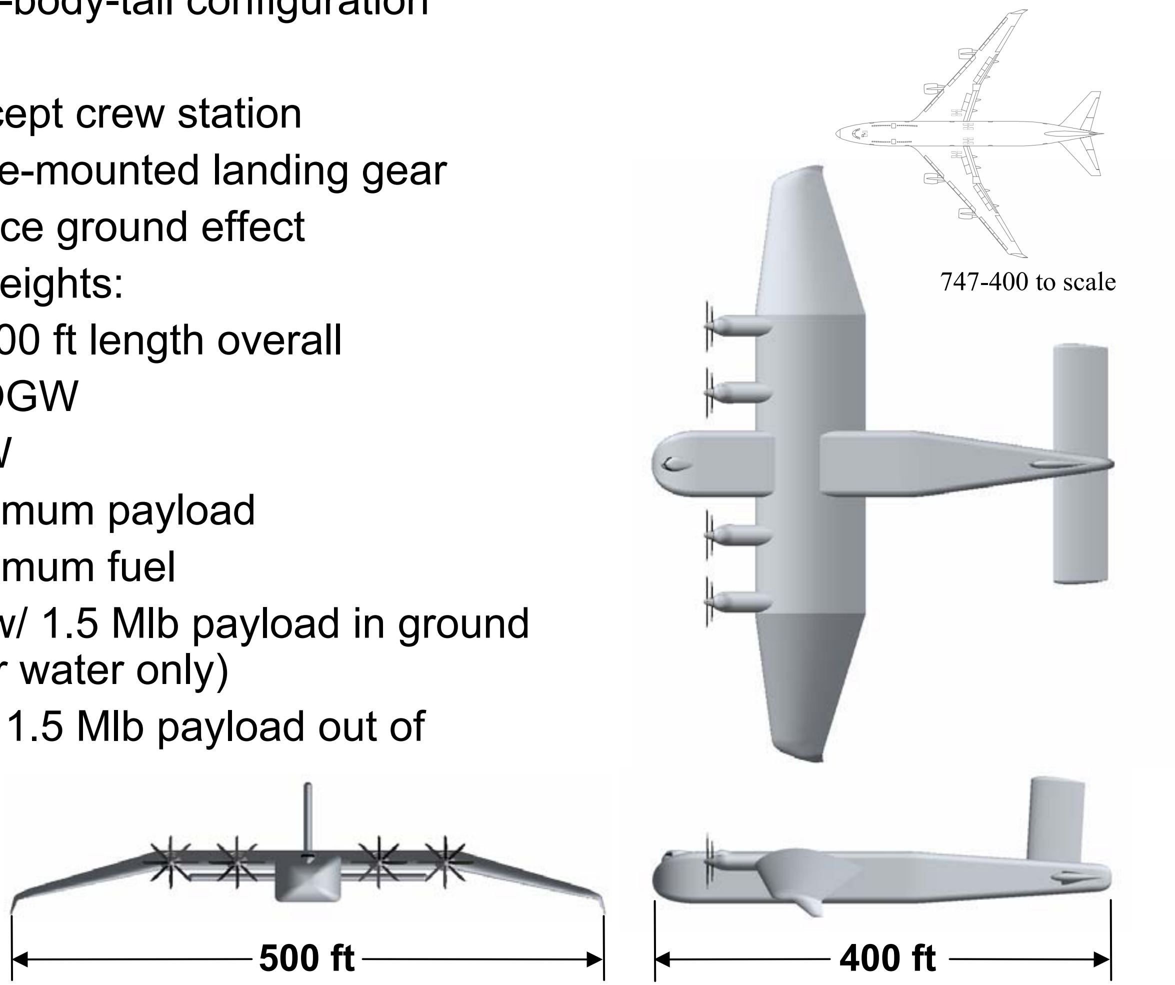






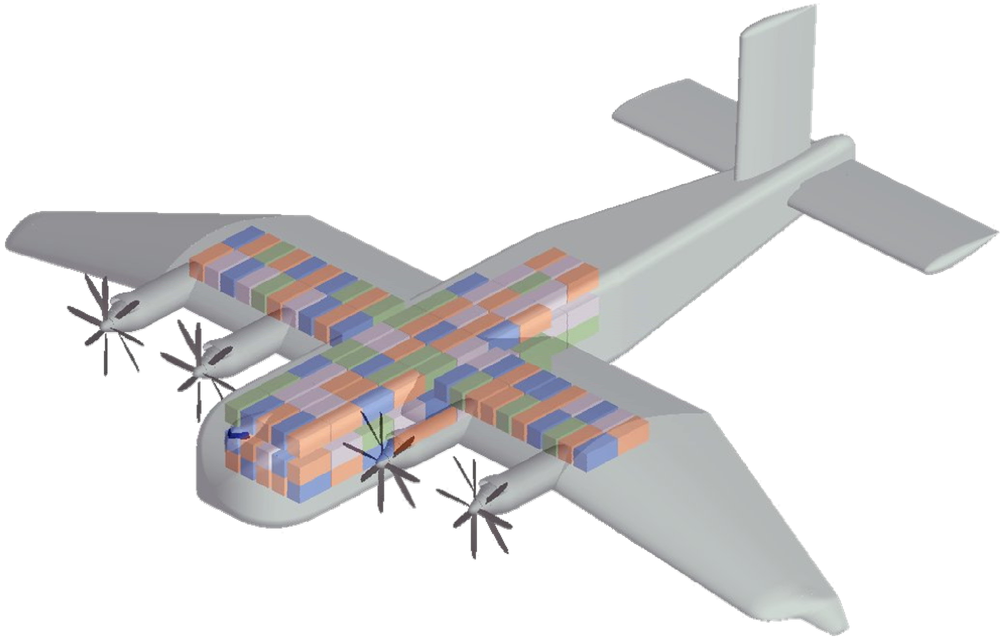
Land-Based WIG “Pelican ULTRA”

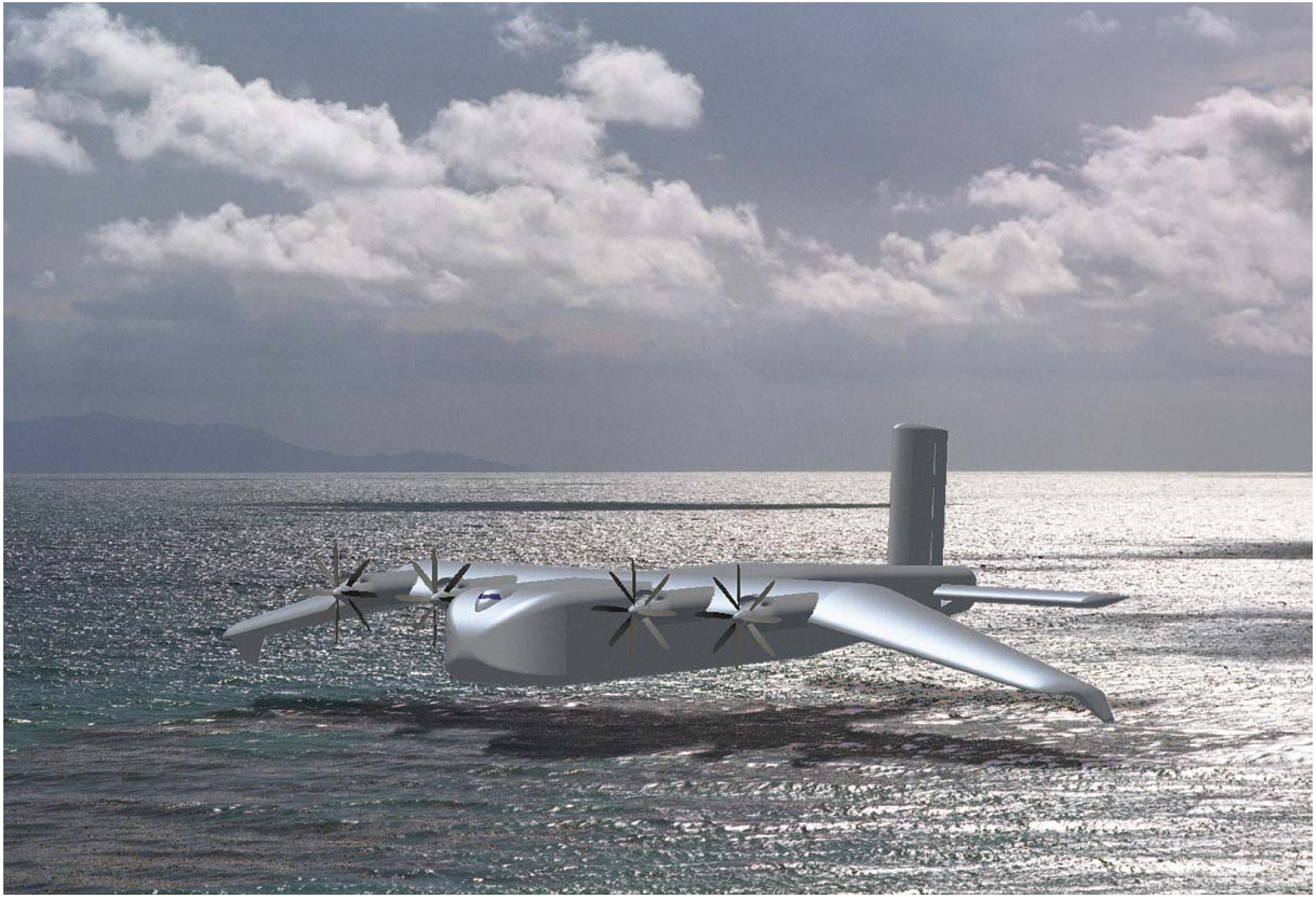
- Conventional wing-body-tail configuration
- Turboprop
- Unpressurized except crew station
- Numerous fuselage-mounted landing gear
- Anhedral to enhance ground effect
- Dimensions and weights:
  - 500 ft span, 400 ft length overall
  - 6.00 Mlb MTOGW
  - 2.16 Mlb OEW
  - 2.80 Mlb maximum payload
  - 2.20 Mlb maximum fuel
- 10,000 nm range w/ 1.5 Mlb payload in ground effect at 20 ft (over water only)
- 6500 nm range w/ 1.5 Mlb payload out of ground effect



Land-Based WIG "Pelican ULTRA"

- High efficiency
  - Low empty weight fraction
  - High L/D
    - 21 out of ground effect
    - 36 at 20 feet
  - High propulsive efficiency
- ISO container cargo
  - Exploits existing ground cargo infrastructure
  - 20 and 40 ft containers
  - Loads through nose into:
    - Main deck (two high)
    - Upper deck
    - Inboard wing

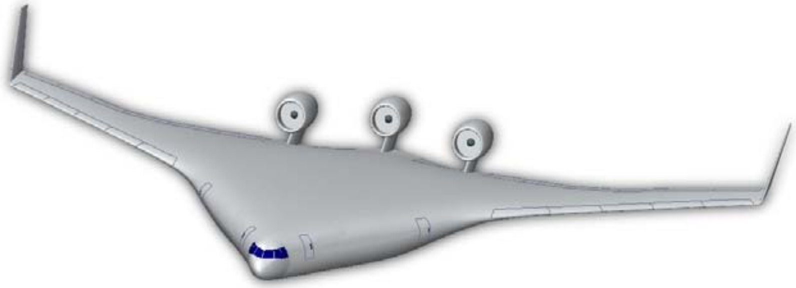


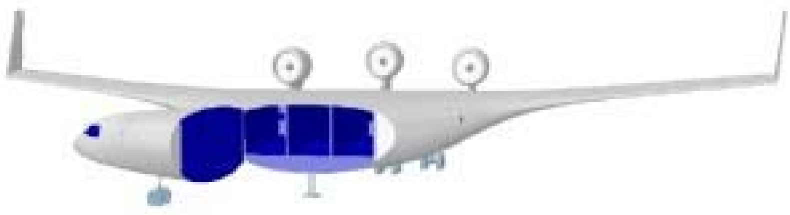


The “Pelican” Container Cargo Aircraft concept has arisen from a request by Gerry Janicki of Market Development to investigate “air vehicles to carry a million pounds a long way”. This paper describes a preliminary effort to identify promising candidates for this mission and to explore the potential of one promising concept we have dubbed “Pelican”.
The Pelican has the potential to create a large new business in commercial cargo transport and to practically resolve a shortfall in military deployment and sustainment capability.

Very Large BWB Freighter

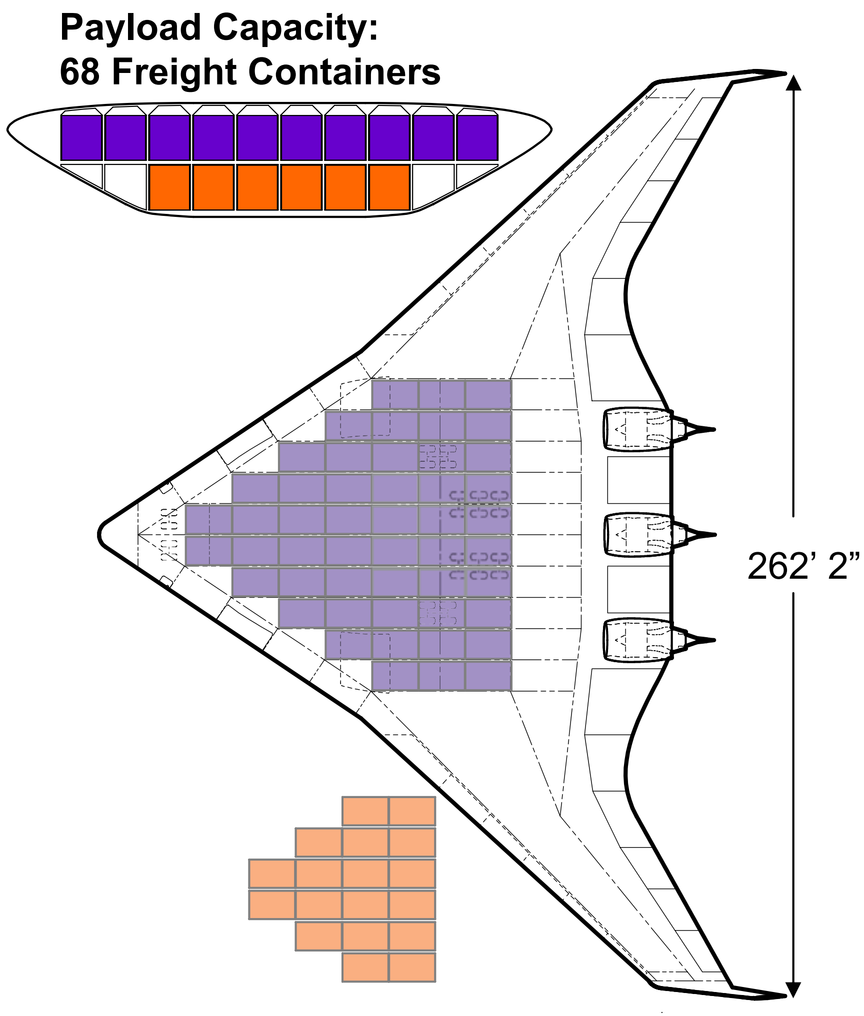
Fits Class VI Airports

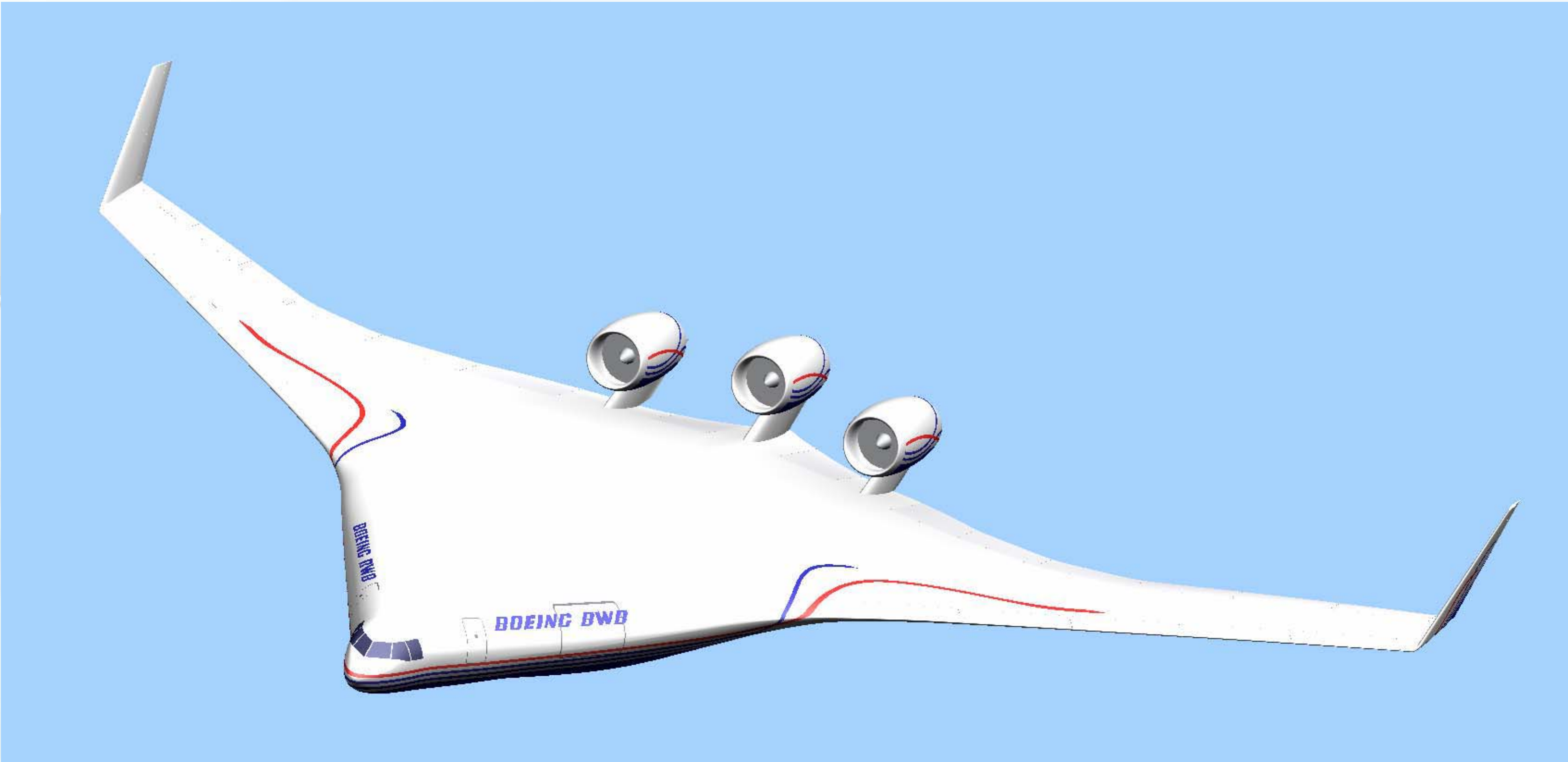




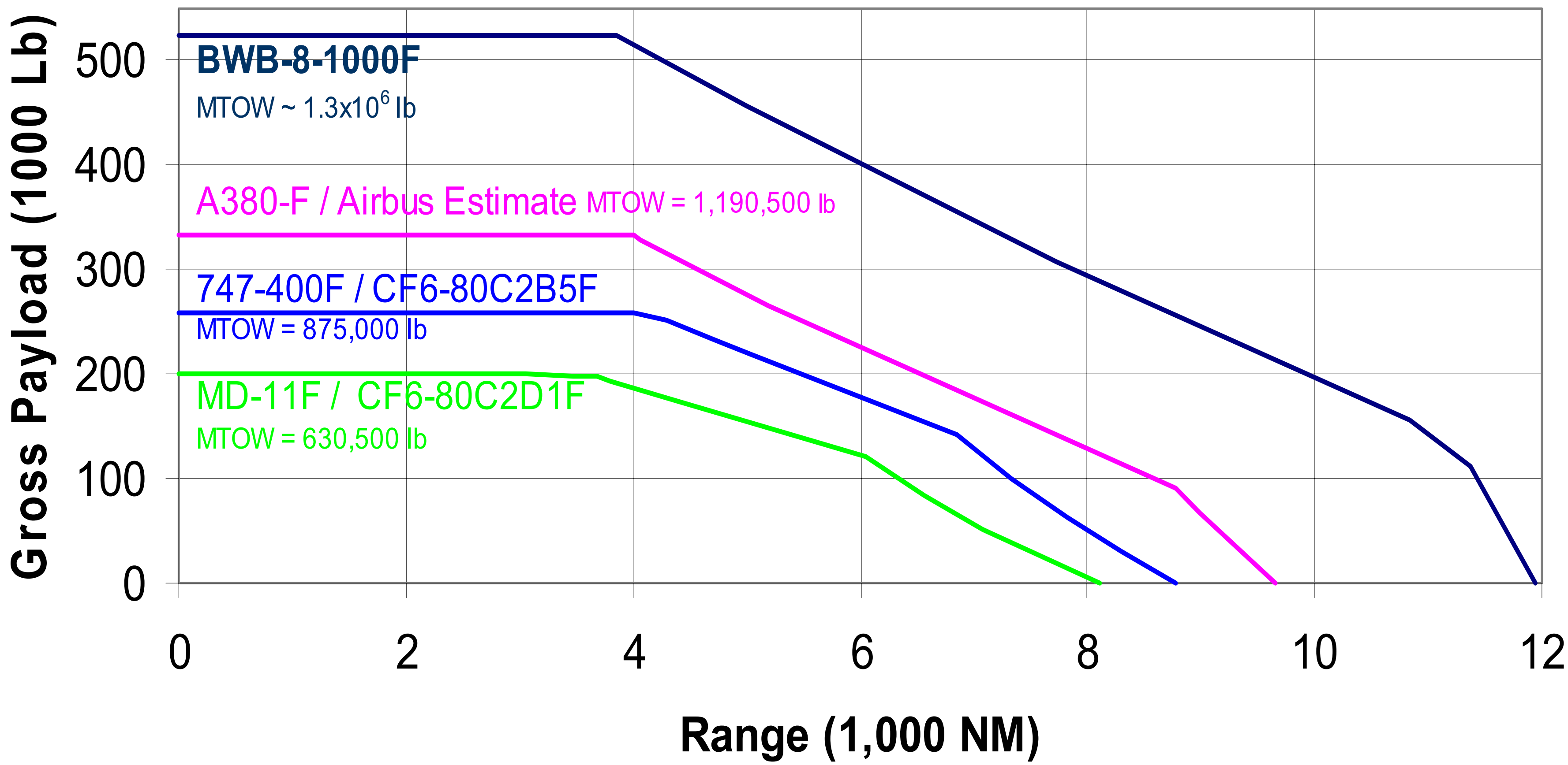
Swing-Nose Loading

Aft Ramp Loading




BOEING BWB
BOEING BWB

Payload-Range Capability



Why Consider Formation Flight?

$$D_i = (1/\pi q e)\,(W/b)^2$$

- Two airplanes flying in proper formation will experience an induced drag reduction on the order of 50 percent, (assuming their combined spanload provides the same e as their individual spanloads).

- An airplane flying near the ground at a height on the order of 10 percent of its wingspan will experience an induced drag reduction on the order of 50 percent via an increase in e > 1.

Induced Drag Sensitivity to Lateral & Vertical Position

$$C_{Di} = (C_{L1}^2 + C_{L2}^2 + 2C_{L1}C_{L2}\sigma_1) / \pi AR$$

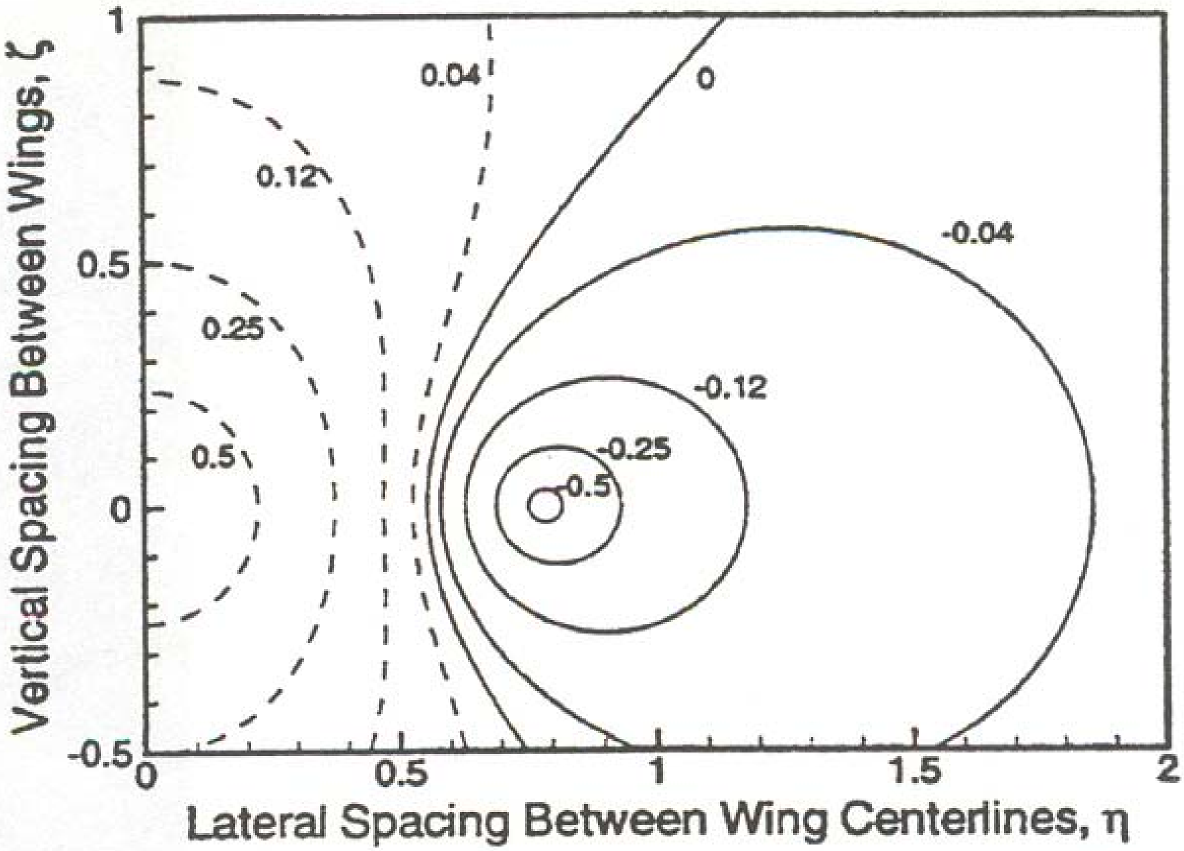


Figure 2. Variation in Mutual Induced Drag (σ_1) With Aircraft Position, Horseshoe Vortex Model.

Ref. Blake & Multhopp
Design, Performance and Modeling Considerations for Close Formation Flight,
AIAA-98-4343.

Rolling & Yawing Moment Sensitivity to Lateral & Vertical Position

$\Delta C_{lk} = (2C_{Lj} / AR)\, \tau_{12}$ $\Delta C_{nk} = (C_{Lj}\, C_{Lk} / \pi AR)\, \tau_{12}$

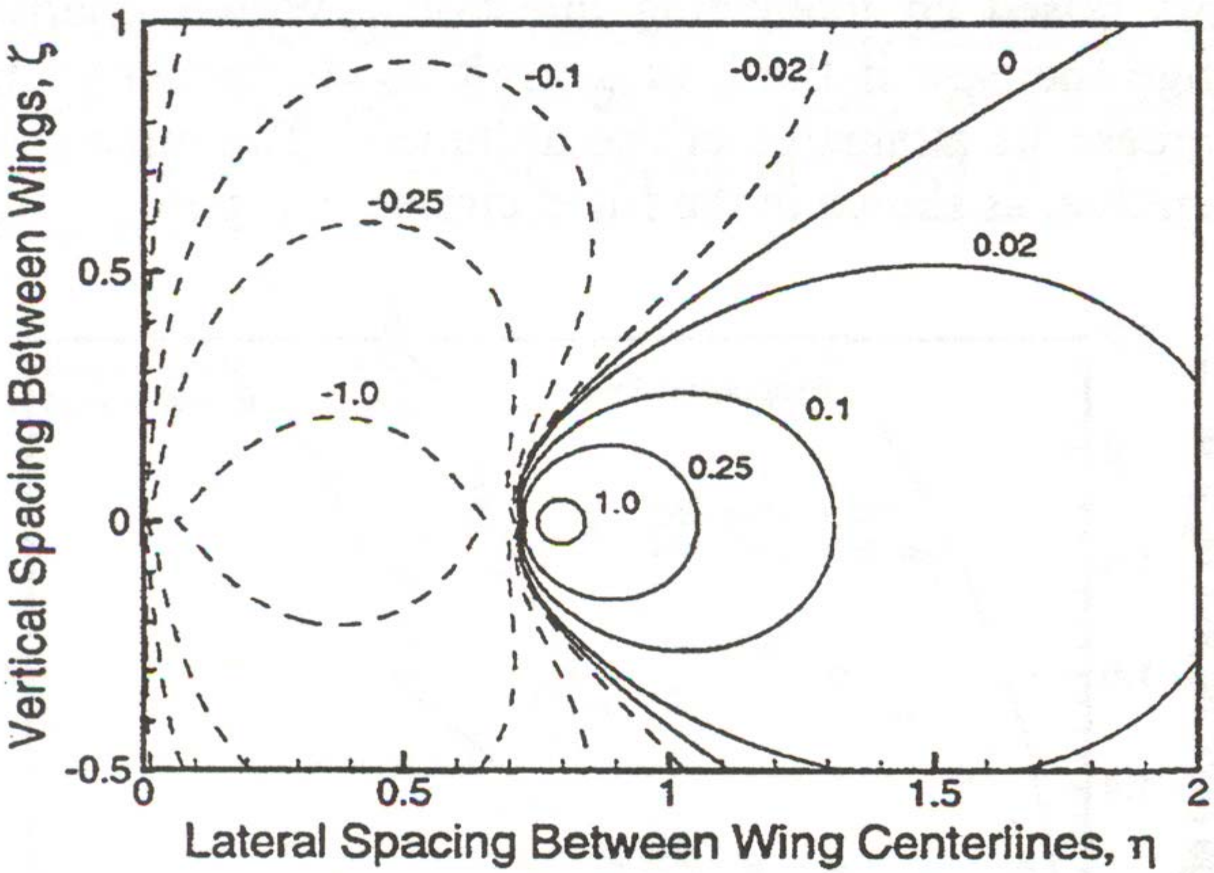


Figure 10. Variation in Rolling/Yawing Moment Factor τ_{12} With Aircraft Position, Horseshoe Vortex Model.

Ref. Blake & Multhopp, *Design, Performance and Modeling Considerations for Close Formation Flight*, AIAA-98-4343

Effect of Lateral Position on Range

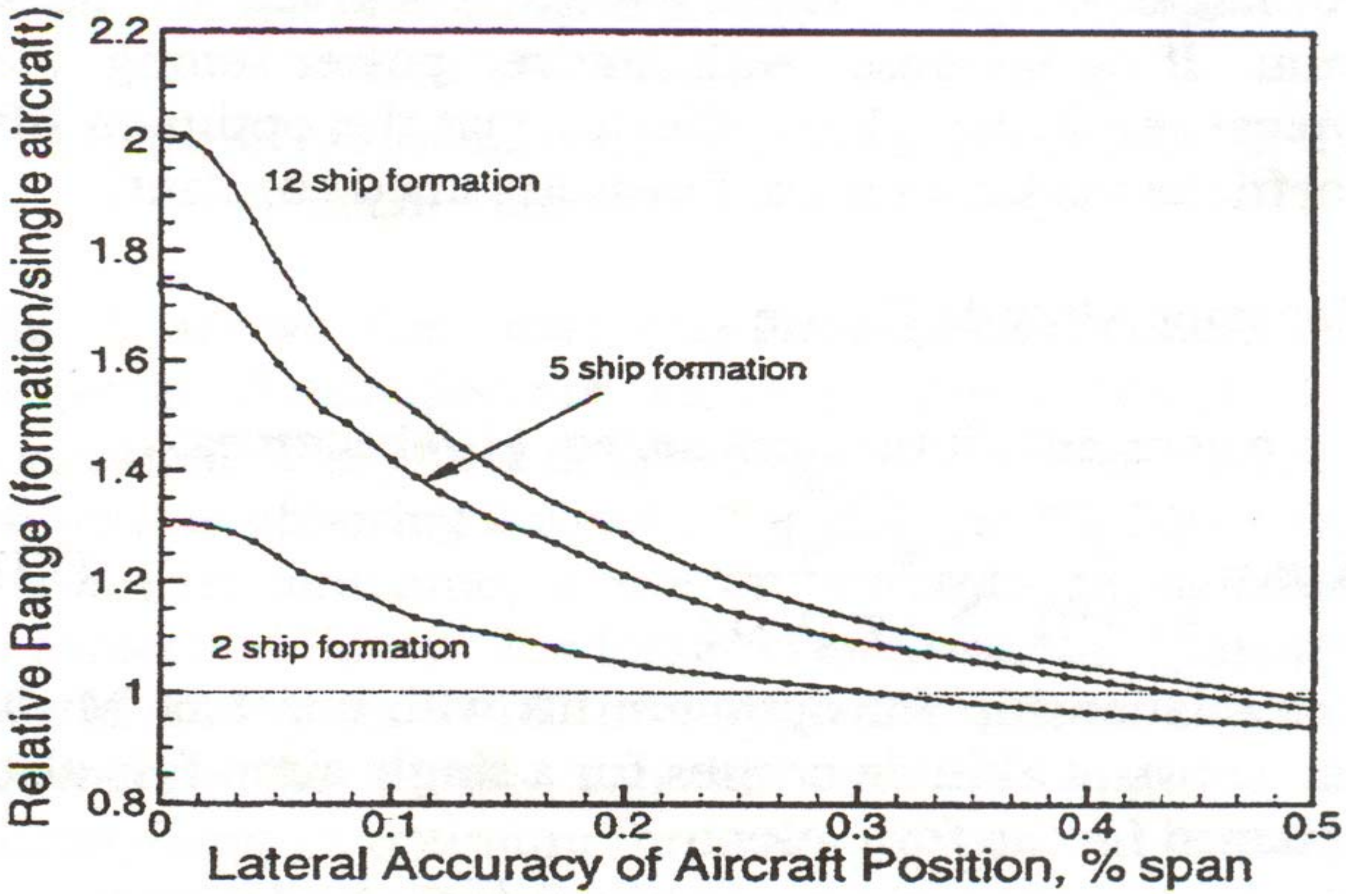


Figure 7. Effect of Lateral Position Accuracy Size on Relative Range. (M=0.85, 10 min rotation)

Ref. Blake & Multhopp, *Design, Performance and Modeling Considerations for Close Formation Flight*, AIAA-98-4343.

Example Spanload for Formation Flight

- Maximum L/D
- Trimmed in pitch and roll

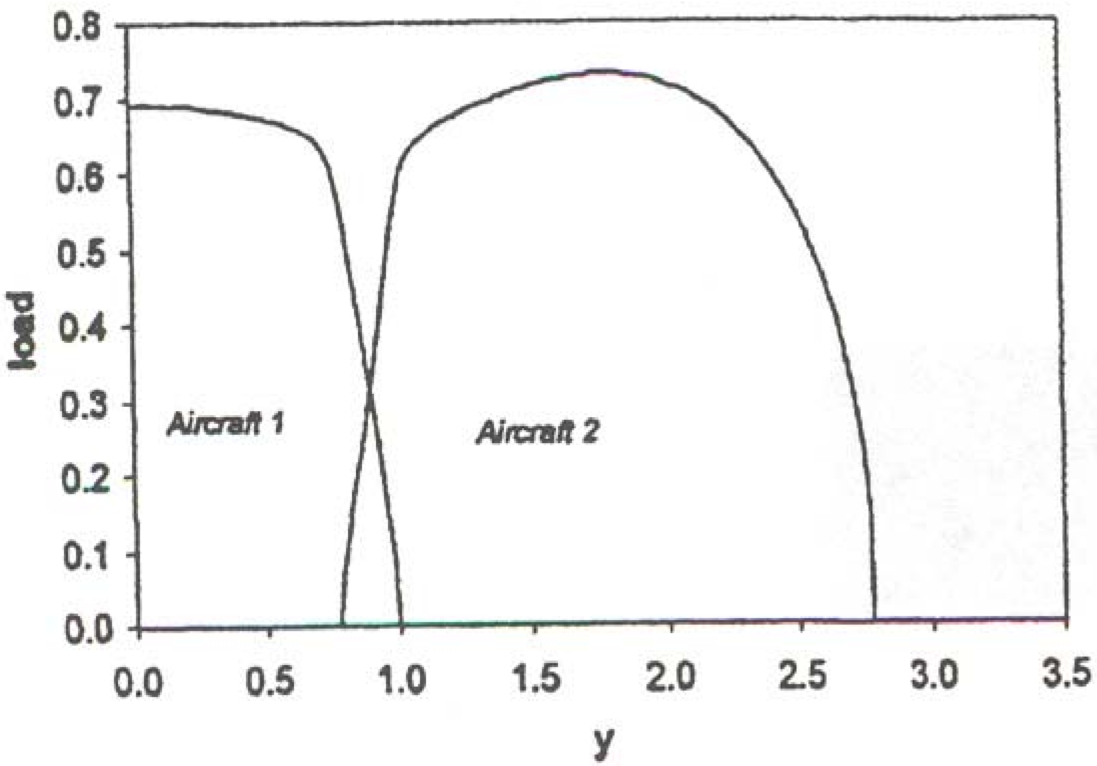


Figure 3. Optimum load distribution *z/b*=0.01, *y/b*=0.89

Ref. Iglesius & Mason, *Optimum Spanloads in Formation Flight*, AIAA-2002-0248

Optimum C_L Distribution for Minimum C_{Di}

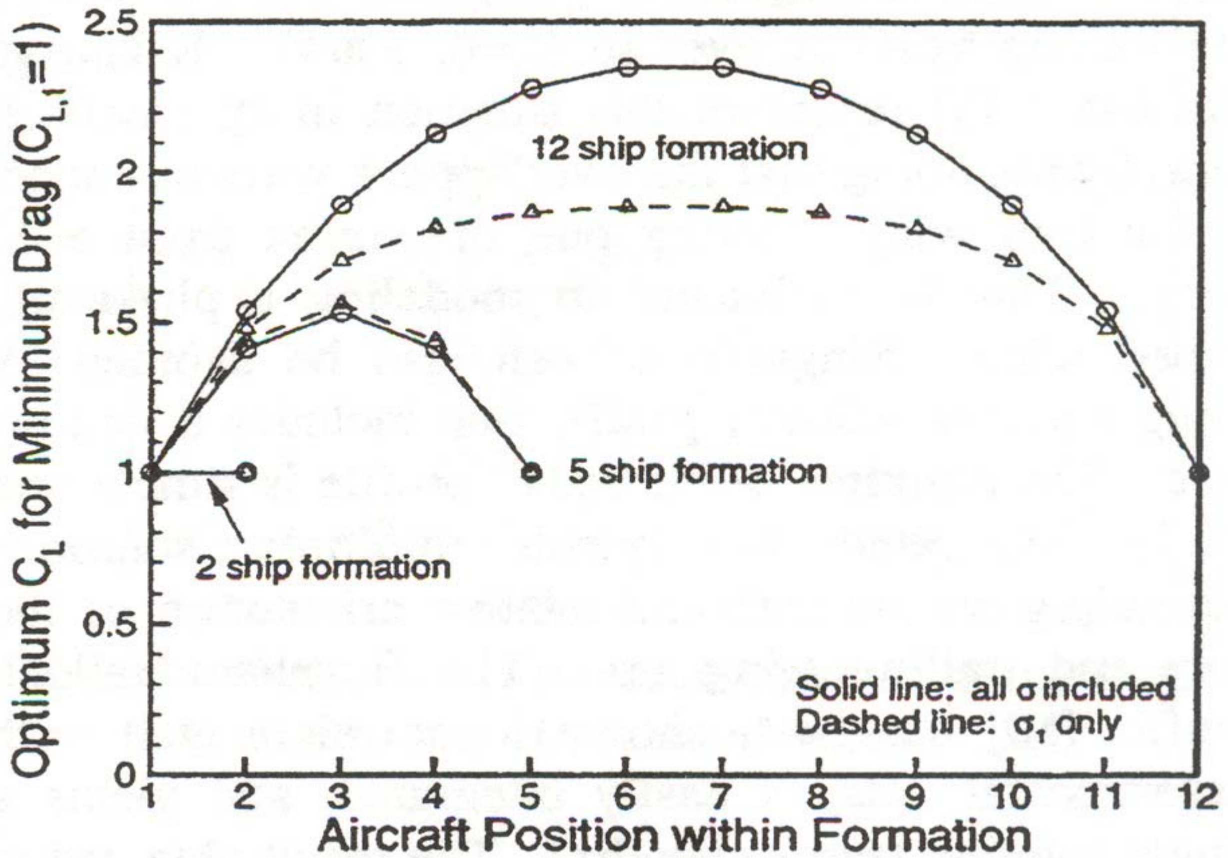


Figure 5. Distribution of Lift Within Formation for Minimum Induced Drag, η=0.85, ζ=0.

Ref. Blake & Multhopp, *Design, Performance and Modeling Considerations for Close Formation Flight*, AIAA-98-4343

Distribution of Power Reduction for 15-Plane Formation

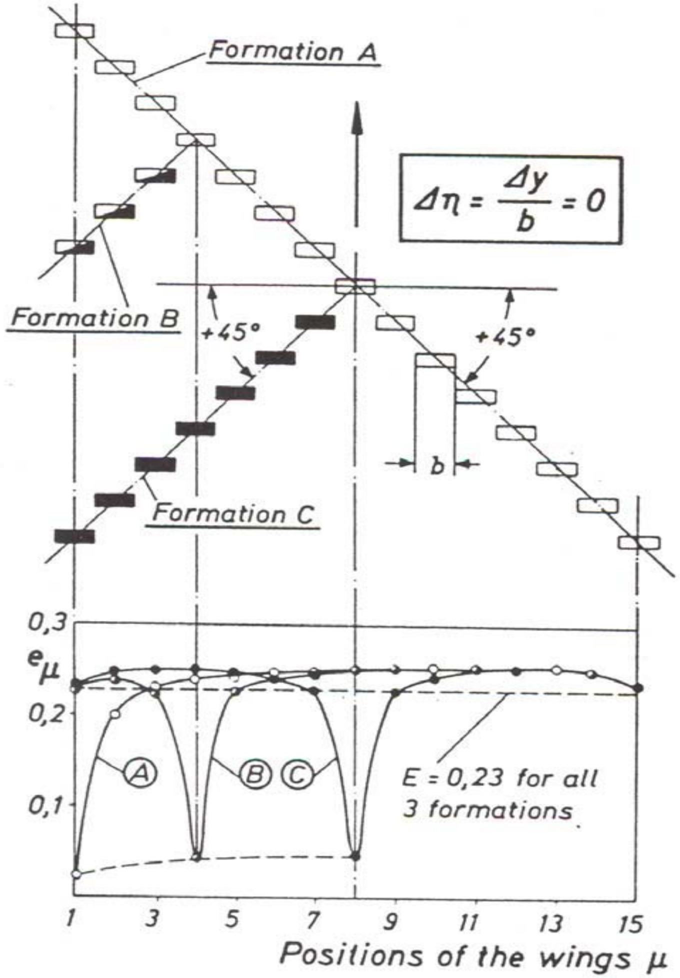


Fig. 6: Distribution of flight power reduction in 45° swept V-shaped formations of n = 15 equal wings at spanwise distance $\Delta y = 0$ and $(c_{Di} / c_D)_0 = 0.5$ for various leading positions n_1.
Formation A = Oblique line, $n_1 = 1$
Formation B = Unsymmetr. formation, $n_1 = 4$
Formation C = Symmetrical formation, $n_1 = 8$.

e_μ = power reduction of individual airplane

E = 0.23 = power reduction of 15-airplane formation

Ref. Hummel, *The Use of Aircraft Wakes to Achieve Power Reductions in Formation Flight,* AGARD CP-584, 1996

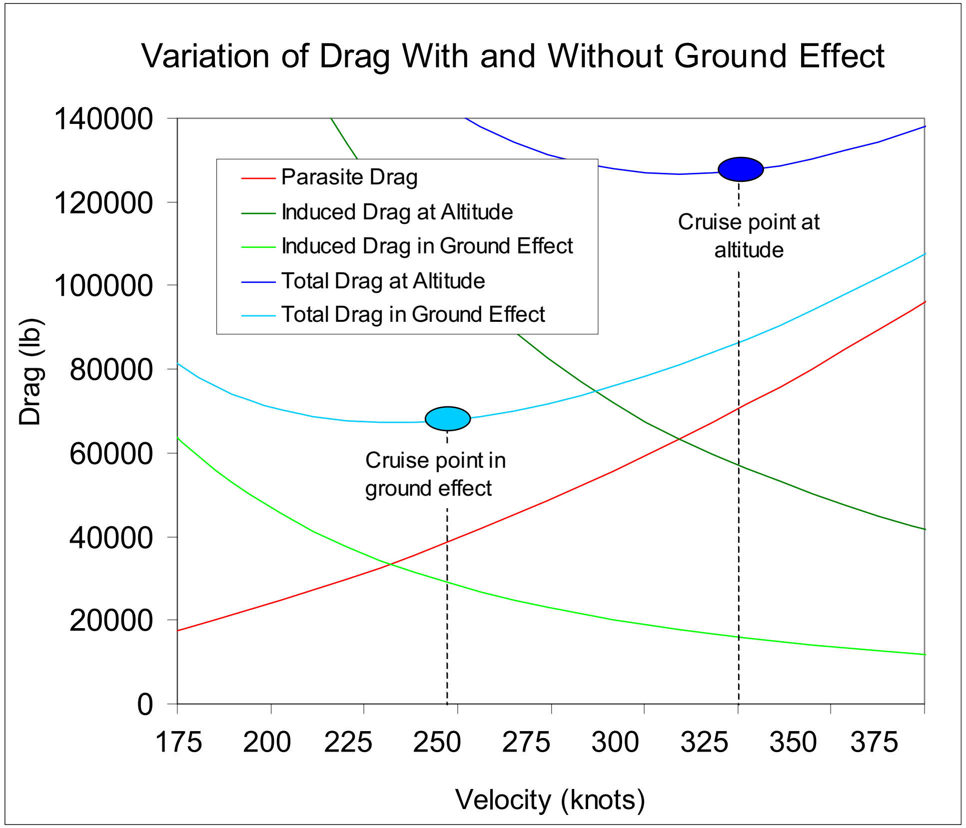
Ground Effect

- Ground effect provides a reduction in induced drag by reducing the downwash via e > 1.0
- Since density is fixed (sea level), this results in a lower optimum speed.

$D = fq + (1/\pi e q)\,(W/b)^2$

The speed for L/D_{max} is

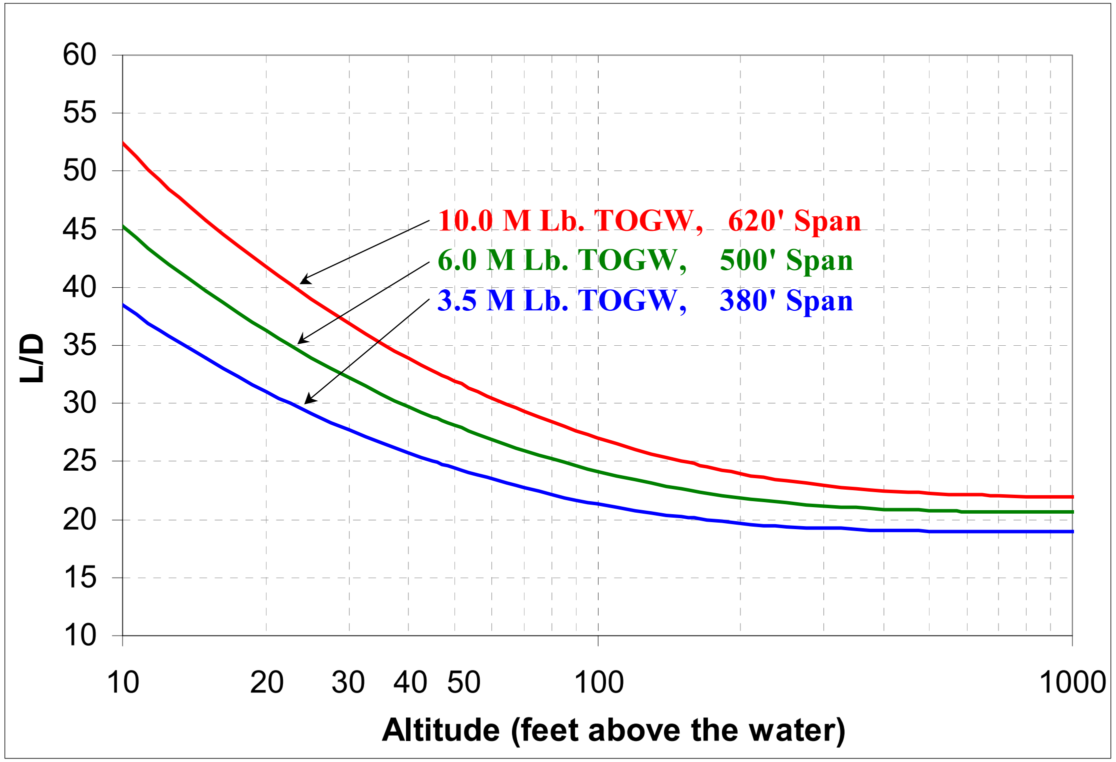
$V^2 = (2/\rho)\,(W/b)\,/(\pi e f)^{1/2}$



Ground effect flight reduces both induced and parasite drag force. Proximity to the ground suppresses wing downwash and reduces induced drag force. By slowing to a speed below the free-air optimum, parasite drag can be reduced more than induced drag is increased.
Airspeeds for the Pelican are chosen at points slightly faster than optimum both in and out of ground effect to improve productivity at a very small cost to efficiency.
Preliminary inviscid computational fluid dynamics analysis has not revealed significant aerodynamic shortcomings in the configuration.

Lift to Drag Ratio

- L/D depends on size and height above ground surface
- Increased size improves ground effect, wetted aspect ratio and Reynolds number
- L/D improves powerfully with reduced height



Autonomous Flight

Conceptual Development Plan

- **Primary goals: formation flight & reduced flight crew**
- Start with single-pilot operation with autonomous backup leading up to fully autonomous operation and autonomous station-keeping
- Technology development
  - Build on current UAV efforts
  - FAA involvement at beginning
    - Regulation development concurrent with system development
    - Certification demonstration requirements
  - Complete operational system simulation
  - Demonstration flight test program
    - Utilize existing UAV autonomous flight experience
    - System demonstration using generic transport aircraft
- Autonomous flight certification
  - Initial certification with generic transport aircraft
  - Initially over water and avoid population centers

Autonomous Flight

Conceptual Objectives/Requirements

1. **Single pilot operation with autonomous backup**
2. **Fully autonomous operation**
   - Operate out of existing airports
   - Operate in existing controlled airspace
   - Flight monitoring/ATC communication from ground station by non-pilot operator(s)
   - Autonomous ground operation (takeoff, landing, taxi)

Autonomous Flight
Conceptual System Elements

- Ground station with human flight monitor/controller and two-way ATC communications
- Satellite link between ground station and aircraft
- Pre-programmed flight plan with GPS way-points
- Differential GPS for terminal operations
- Cockpit view high-res video for terminal/landing operations

Airplane Design for Formation Flight

- Autonomous station-keeping
  - direct side force desirable
- Adjustable span-load for trim & efficiency in and out of formation flight mode
- Design-trade issues
  - Optimum span-load for free flight is “triangular”, with a significantly lighter loading at the wing tips than elliptic. This reduces the wing root bending moment, and hence the structural weight.
  - The optimum span-load for formation flight has an unusually high load outboard (well beyond elliptic), and it is asymmetric.
  - Ride quality for downstream formation members could be critical for passenger applications.

Design for Formation Flight (cont.)

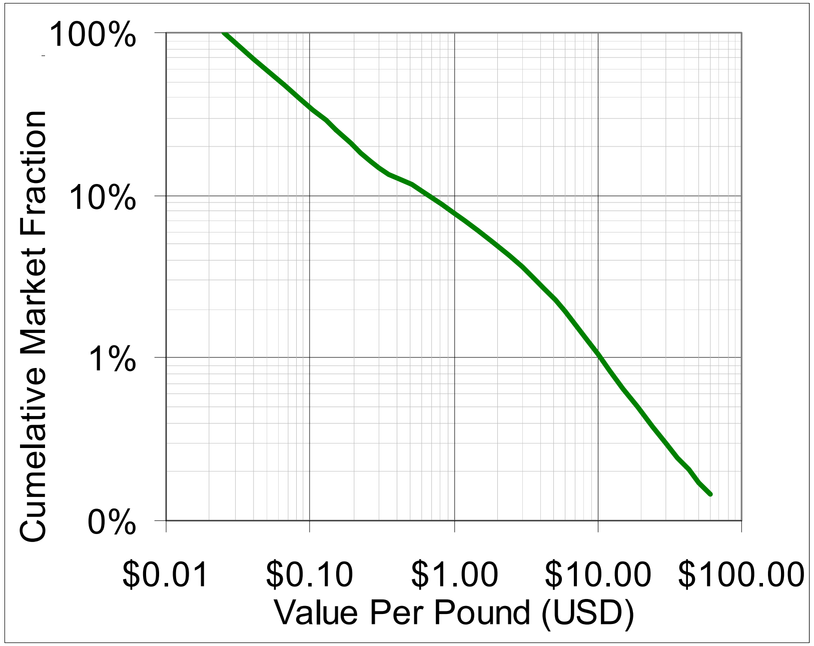
- The reduction of induced drag occurs via an increase in effective wingspan.
- Maximum L/D occurs when profile drag equals induced drag, and profile drag does not change with formation flight.
- Thus maximum L/D must be achieved by flying at a correspondingly higher lift coefficient when in the formation mode.

Dedicated Freighter vs Adapted Military or Commercial Airplane

- Airplane price
  - non-recurring & recurring cost
- Utilization
  - freighter 5 hrs/day, commercial airliner 14 hrs/day
- Efficiency
  - $/ton-mile cash-related operating cost
- Freighter-unique capability
  - e.g. out-sized payload, very large airplane
- Future requirements and unknowns
  - airplanes last 30 t0 50 years
- To date, a dedicated freighter business case has not closed

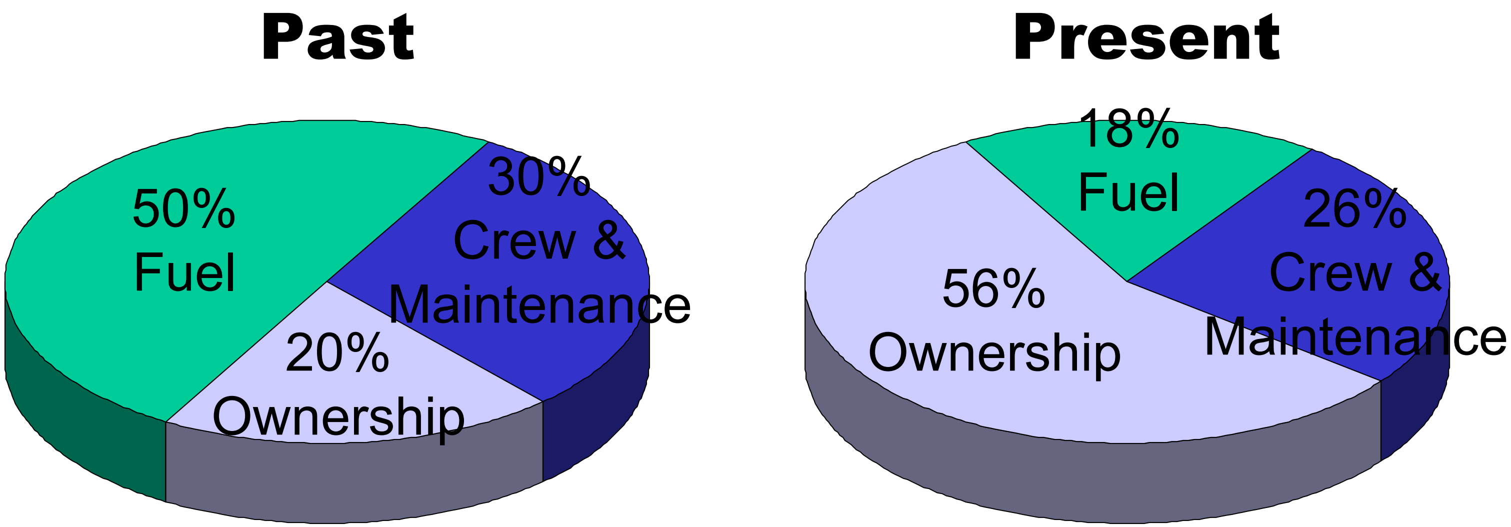
Market - Size

- Total cargo market in 2020 is approximately 70 Trillion ton-miles per year
  - Capacity of 250,000 747-400's
- Market fraction can be estimated on the basis of cargo value per pound
  - 25% of market worth > $0.10/lb
  - 8% of market worth > $1.00/lb
  - 1% of market worth > $10.00/lb
- Combined with Total Distribution Cost analysis, this data can provide rough order of magnitude market size estimate

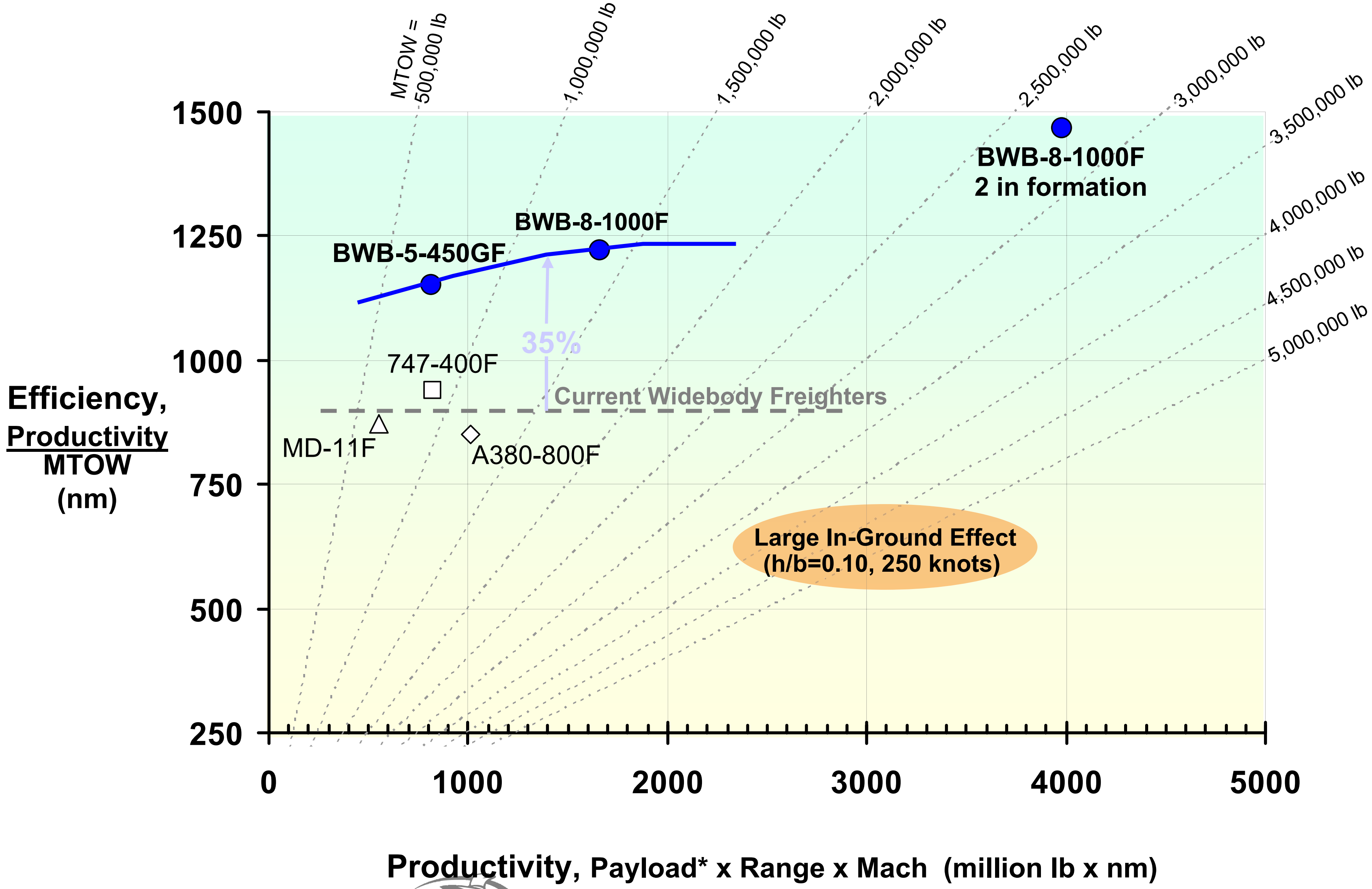


Major Operating Cost Fractions Have Changed

- Need for increased utilization of airplanes
  - drives modular design
- Cost of ownership has become the major element of operating cost



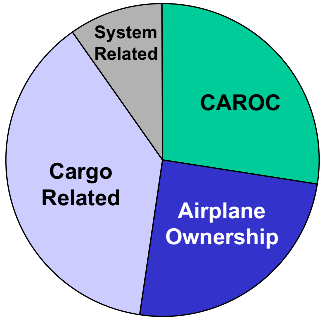
Freighter Efficiency vs Productivity



Cargo Delivery Schedule/Cost Assumptions

Current Boeing OPCOST Model

	Drop off package at airport	Load on plane	Fly	Unload plane	Airport destination
Duration:		x hrs	6¾ hrs	x hrs	Total: **7+ hrs**
Costs:					



Boeing OPCOST economics includes:
- Fly
- Load & unload plane
- Cargo Commissions
- Advertising & Publicity
- Reservations & Sales
- General & Administrative

Today's FedEx Package Delivery

	Drop off package at pickup location	Truck	Unload truck, sort and load on plane	Fly	Unload plane, sort and load on plane	Fly	Unload plane, sort and load on truck	Truck	Drop off at destination
Duration:		2 hrs	2 hrs	3 hrs	3 hrs	3 hrs	2 hrs	3 hrs	Total: **18 hrs**
Costs:									

Ships

	Pick up ISO at shipper and load on truck	Truck	Unload ISO from truck, sort and load on ship	Sail	Unload ISO from ship, sort and load on truck	Truck	Drop off ISO at destination
Duration:		3 days	7 days	10 days	7 days	3 days	Total: **30 days**
Costs:							

Catalina Delivery Concept

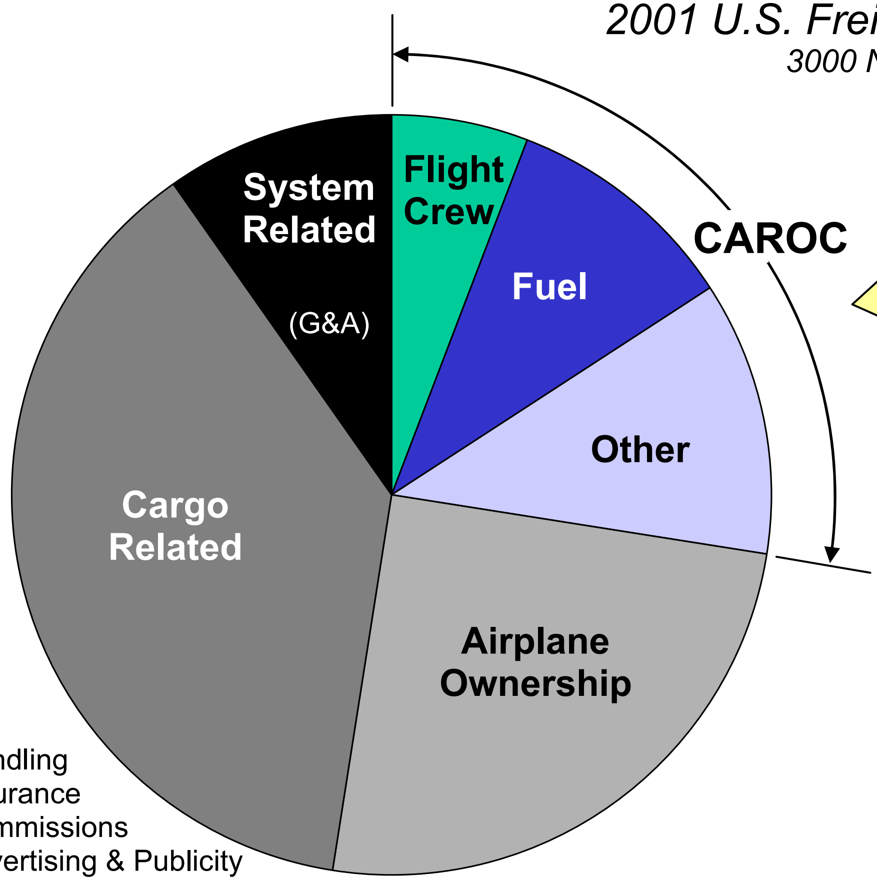
	Pick up container at shipper and load on truck	Truck	Unload truck and load on Catalina	Fly	Unload Catalina, sort and load on truck	Truck	Drop off container at destination
Duration:		2 hrs	2 hrs	10 hrs	2 hrs	3 hrs	Total: **19 hrs**
Costs:							

Total Operating Cost Breakdown

Freighter Example

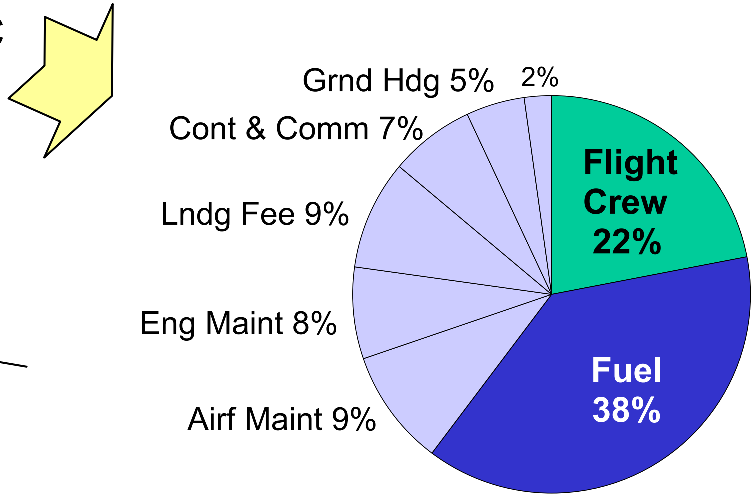
2001 U.S. Freighter Rules

3000 NM



- Handling
- Insurance
- Commissions
- Advertising & Publicity
- Reservations & Sales

Total Operating Cost



Cash Airplane Related Operating Cost (CAROC)

Cash Airplane Related Operating Costs

2001 U.S. Freighter Rules

9.0 lb/ft³ - 3000 NM