Preliminary MIPCC-Enhanced F-4 and F-15 Performance Characteristics for a First-Stage Reusable Launch Vehicle

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Code RA/Propulsion Group/NASA-Dryden

Air Breathing Boost Stage

Reducing the cost of access to space

Traditional motivations for air-breathing boost stages

1.) Efficiencies – Higher Isp's/Performance

2.) Reusability/Reliability

Wings

Air Launch Assist / Justifications

1.) Launch Site Flexibility – From any large runway to orbit

2.) Reduction in launch infrastructure costs

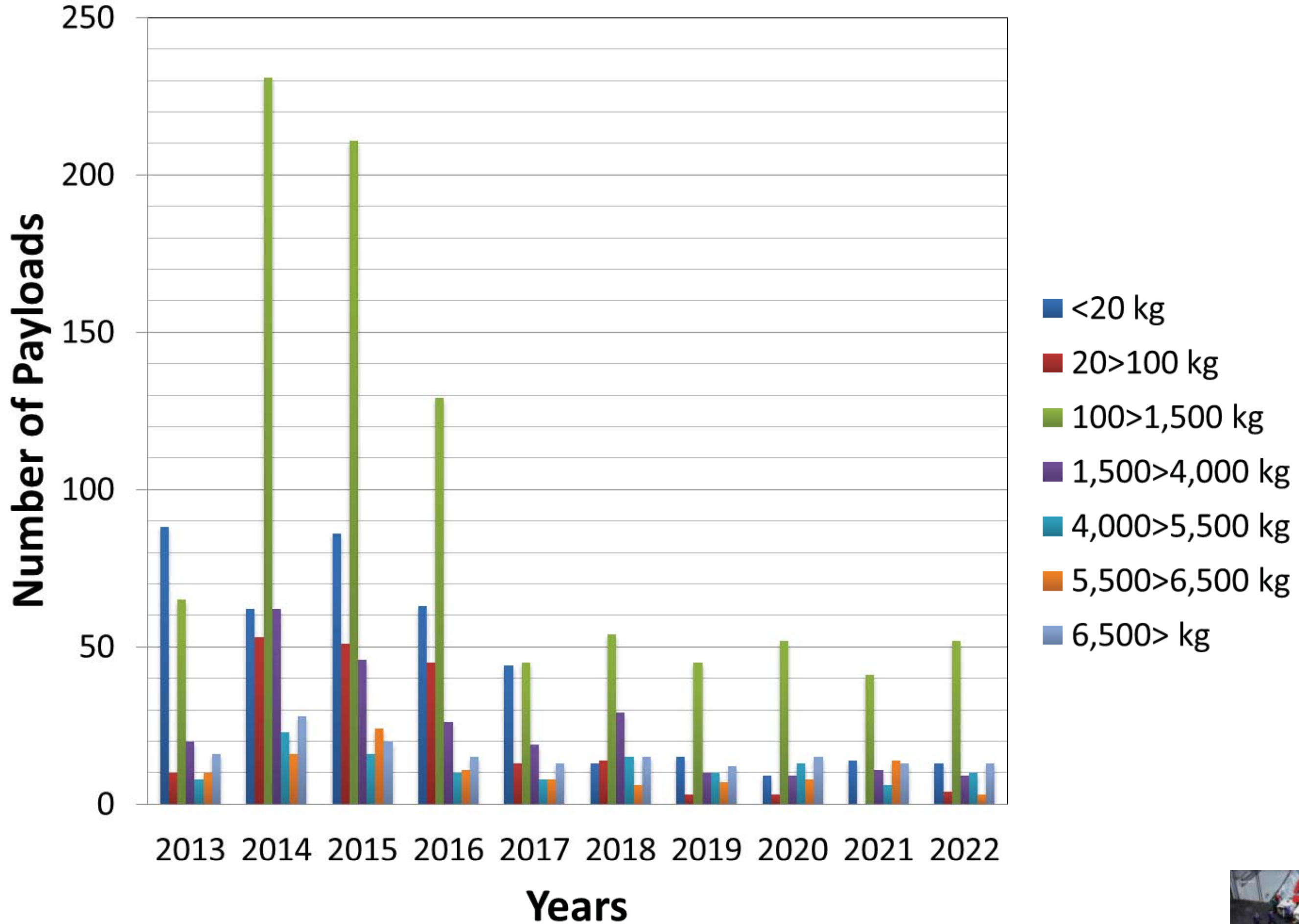
3.) Launch window availability in time and orbital inclination

Limited number of launch pads drives sequential launches

Launch Market Projection – Payloads by Mass (kg)

Year 2013 market studies indicate demand for small payloads

Small payloads capture large percentage of launch market

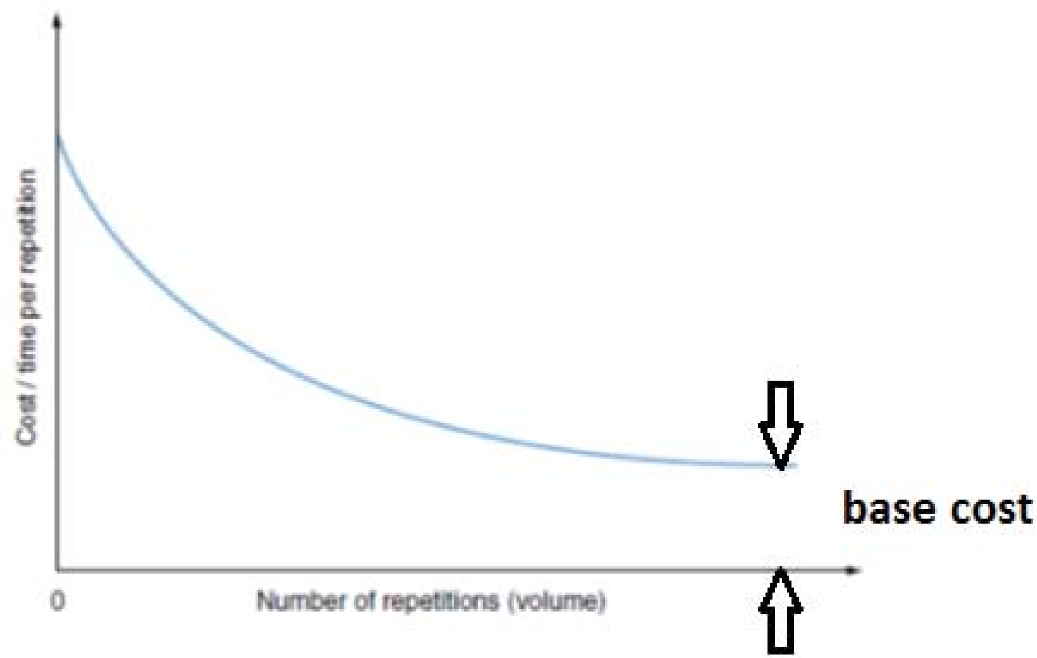


Source: AeroSpace America, June 2013, Teal Group, mcaceres@tealgroup.com, pages 22-24

Reduction of Base Cost

Propose a motivation based on power (watts).

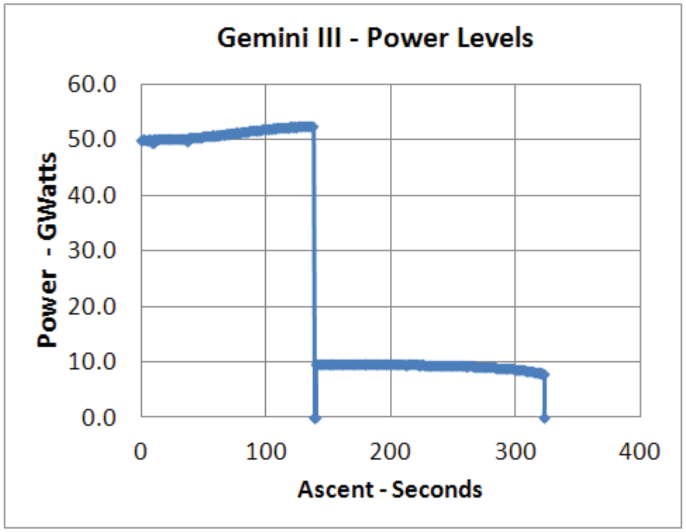
This justification affects the supply chain of the launch device, and ultimately the long term system base costs.

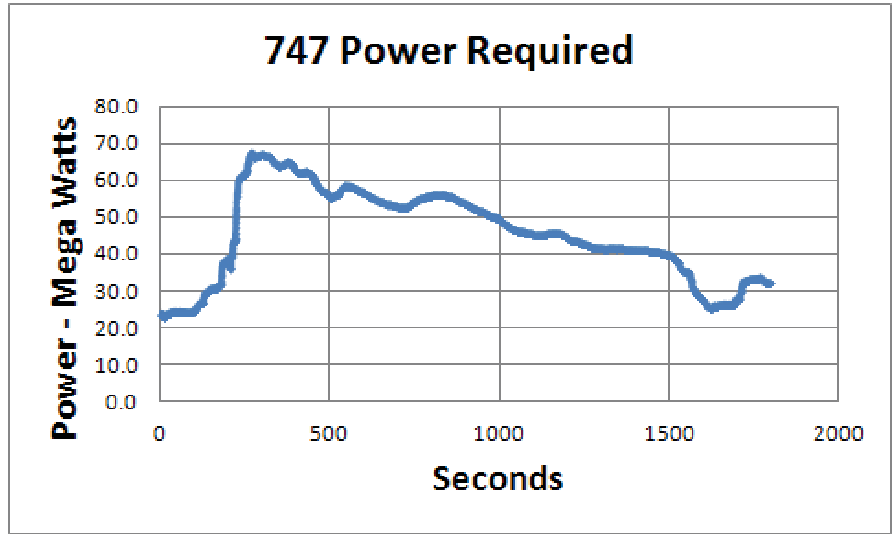


GigaWatts vs. MegaWatts

TWO ORDERS OF MAGNITUDE to achieve similar energy states

These orders of magnitude are reflected in every portion of the launch system operating costs





GigaWatts

Energy State: 64.14 Btu/lbm

Weight @state 234,262 lbsm

25,876 feet

Mach 1.23

time to climb ~63 seconds

TIME

MegaWatts

Energy State: 64.75 Btu/lbm

Weight @state 497,000 lbsm

40,000 feet

Mach 0.85

time to climb ~16 minutes

Note: 747 consumed about 15,000 lbm fuel during climb, the Titan consumed about 106,000 lbm

Reusability and Reliability

Rocket Engine: Merlin 1C

~100 cycles?

~50 lifetime hours?

94,000 lbf Thrust (SL)

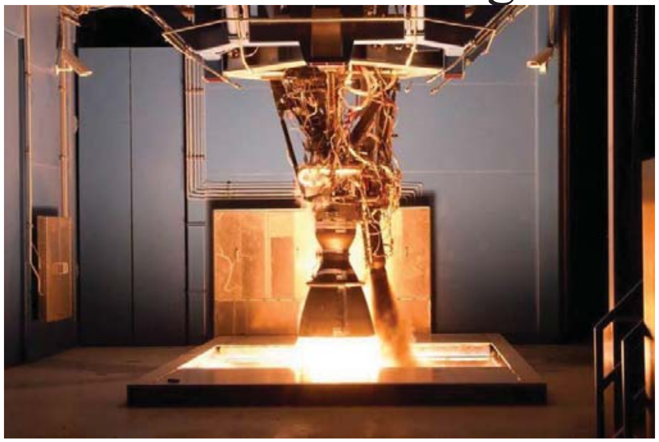
Weight 1,380 lbm

Pressure ~ 1000 psi

Temp ~3500 K

Life Expectancy ?

Power Level – 8 GigaWatts



Turbojet Engine: F-100-229

~4000 cycles

~3000 average lifetime hours

29,000 lbf thrust (SL)

Weight 3740 lbm

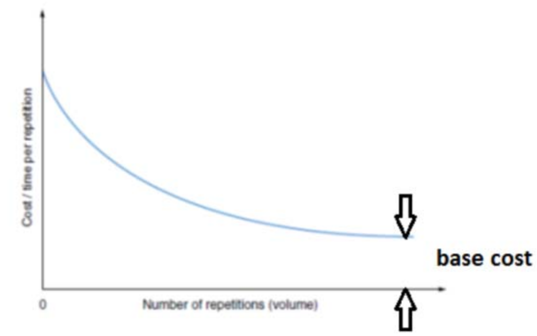
Pressure -300 psi/448 psi

Temp: 2000 K

Life Expectancy of 16 years

Power Level - ~20 MegaWatts

Air Breathing/Air Launch



Observations:

1.) Potential repetitive small payload market

Quickly advance down the learning cost curve

2.) Potential highly reusable and reliable booster stage

Reduction in recurring base line costs

3.) Cost reducing benefits from airport-like launch infrastructure

= Potential to significantly reduce cost of access to space

Current NASA-Dryden Air Launch Efforts

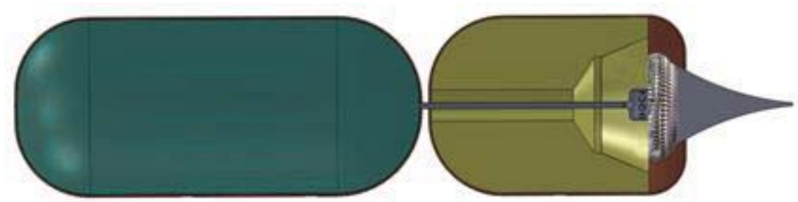
1.) Small Air Launch Vehicle to Orbit

F-15 Assisted Rocket Launch to LEO

DARPA Requested F15 CONOPS support/planning

2.) HUSB – Hybrid Upper Stage Booster – AeroSpike Nozzle

3.) ALFATA – Air Launch From A Towed Aircraft



Advanced hybrid engine upper-stage for small and nano-satellite launchers with high-performance, aerospike nozzle for increased specific impulse

Reference: 100-lbm payload /100-nm orbit/28 deg

Solid Fueled Launched @ Mach 3, 70kft

Weight class, lbm	First-stage weight, lbm	First-stage thrust, lbf	Second-stage weight, lbm	Second-stage thrust, lbf	Payload to orbit, lbm
5000	4117	16650	711	2843	210
10000	8233	33300	1421	5686	432
15000	12350	49950	2132	8528	657
20000	16467	66500	2843	11371	882
25000	20583	83250	3553	14214	1095
30000	24700	99900	4264	17057	1330

Table 4. Payload delivered to a 100-nm circular orbit by a generic two-stage solid rocket system from a launch point of Mach 3.0 at an altitude of 70,000 ft.

Liquid Fueled Launched @ Mach 3, 70kft

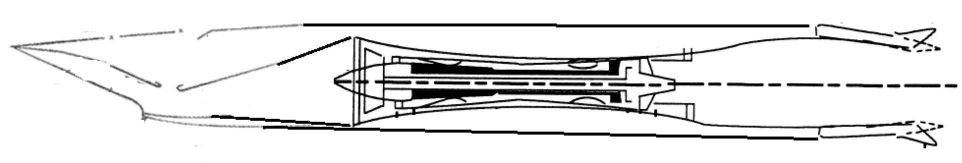
Weight class, lbm	First-stage weight, lbm	First-stage thrust, lbf	Second-stage weight, lbm	Second-stage thrust, lbf	Payload to orbit, lbm
5000	4116	16650	710	2843	243
10000	8350	33300	1196	4786	563
15000	12525	49950	1795	7179	844
20000	16700	66700	2293	9572	1133
25000	20875	83250	2991	11965	1421
30000	25050	99900	3589	14358	1711

Table 6. Payload delivered to a 100-nm circular orbit by a generic two-stage liquid-fueled rocket system from a launch point of Mach 3.0 at an altitude of 70,000 ft.

Reference: Kloesel, Kurt J., Nalin A. Ratnayake and Casie M. Clark. "A Technology Pathway for Airbreathing, Combined-Cycle, Horizontal Space Launch Through SR-71 Based Trajectory Modeling." NASA: Dryden Flight Research Center. Retrieved: 7 September 2011.

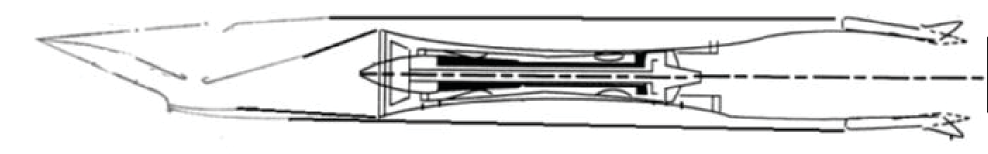
Mass Injection Pre-Compressor Cooling (MIPCC)

Atmosphere
Nitrogen/Oxygen



Thrust

Substitute Atmosphere
Water Vapor/Oxygen

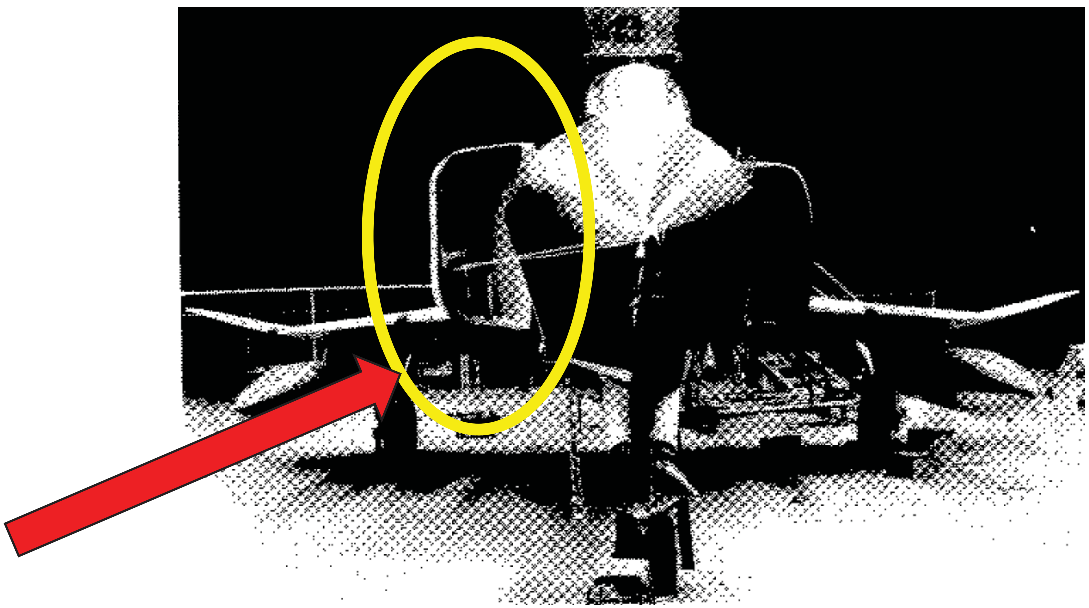


Thrust

Source: W.F. Imfeld, AIAA No. 74-1061, The Development Program for the F-15 Inlet

Pre-Compressor Cooling Timeline

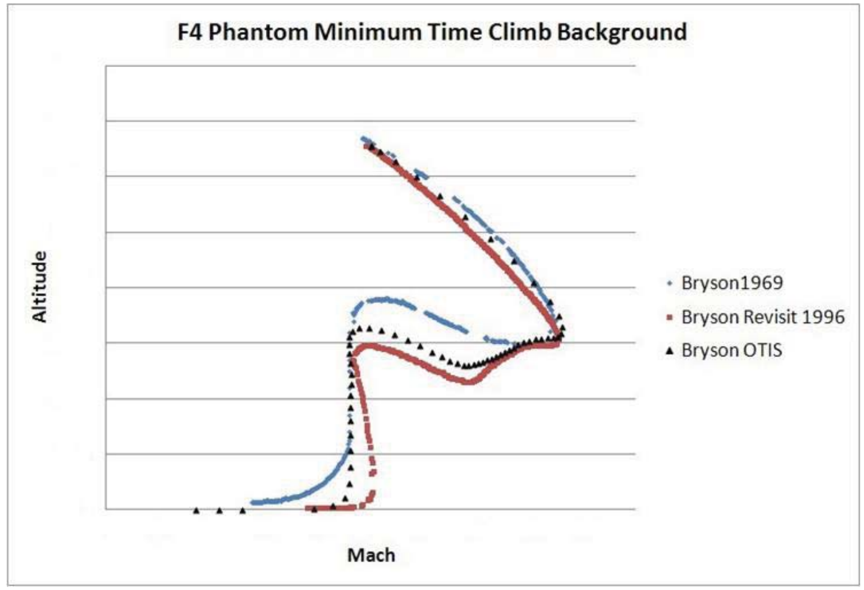
- **Early 1950's NACA Studies**
- **1957-58 General Dynamics F-106, J57&J75 AEDC engine testing**
- **1958 Vought F8U-3/J75 flight testing (Mach 2.2)**
- **1962 McDonnell F4H-1 Operation SageBurner**
- **1972-1975 General Dynamics Operation Peace Jack RF-4X (F-4E)**
- **2006 DARPA RASCAL: Responsive Access Small Cargo Affordable Launch**
  - **F100 Engine testing**



General Dynamics F-4E with MIPCC Cardboard Mockup

Reference: F-4 Phantom II – Operation High Jump - 1962

- **F-4 Phantom II Minimum Time to Climb OTIS simulations**
  - **Re-weighted F-4 Phantom II Minimum Time to Climb**



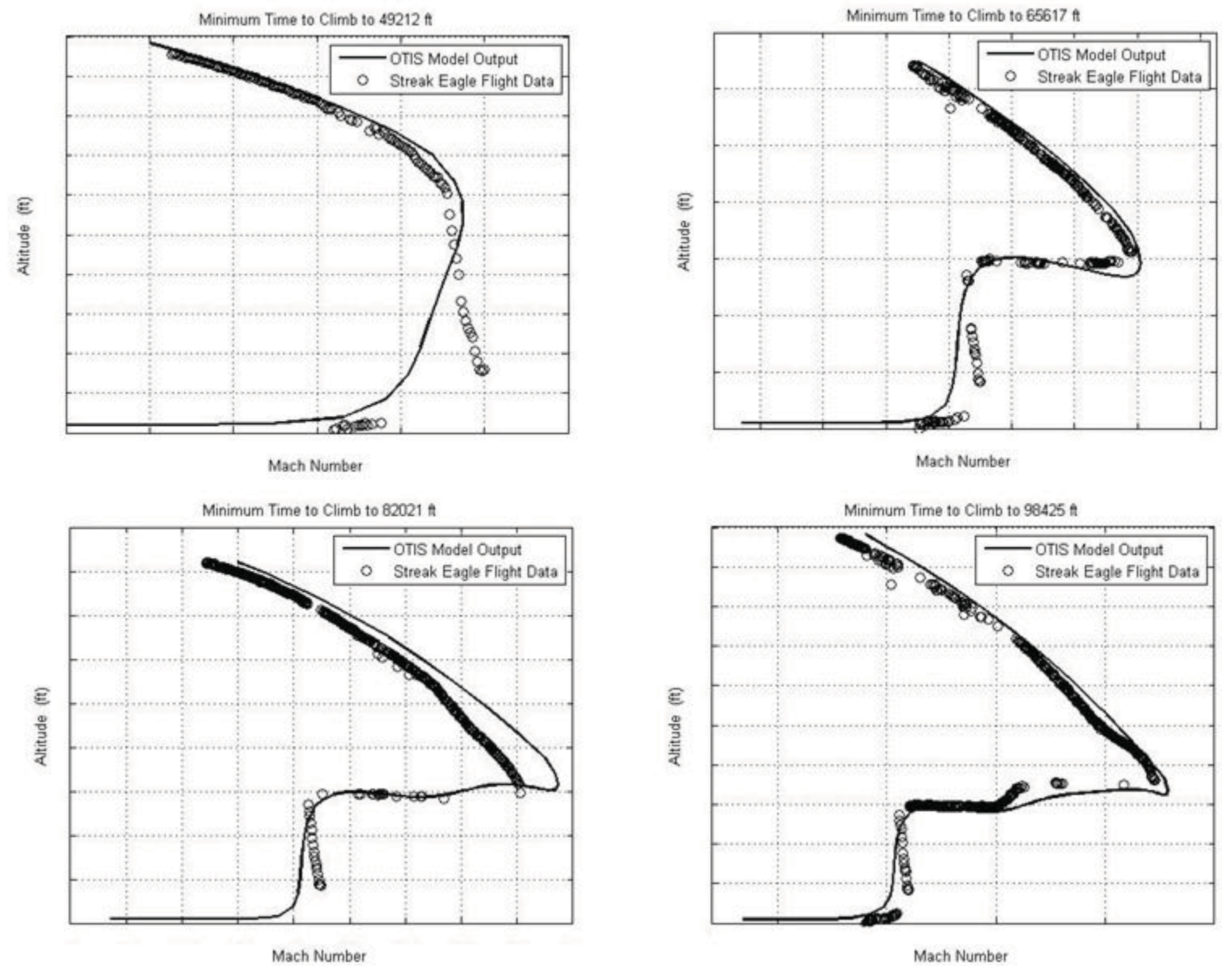
Altitude (ft)	Record (sec)	|%| Difference Original Simulation	|%| Difference Reweighed F-4
9,840	34.523	36	4.1
19,700	48.787	30	2.4
29,500	61.629	30.7	2.1
39,400	77.156	36.2	4.7
49,200	114.548	33.4	3.7
65,600	178.5	37.8	0.8
82,000	230.44	41.3	1.09
98,400	371.43	N/A	3.7

Reference: F-15 Streak Eagle - 1975

The F-15A Streak Eagle Minimum Time to Climb OTIS simulations

- Pilots Majors Willard R. Macfarlane, David W. Petersen, and Roger J. Smith
- OTIS simulations compare favorably

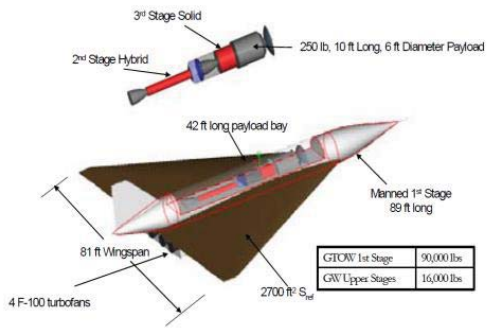
Altitude (ft)	Time, (sec)
9,842.52	27.57
19,685.04	39.33
29,527.56	48.86
39,370.08	59.38
49,212.60	77.02
65,616.80	122.94
82,021.00	161.02
98,425.20	207.80

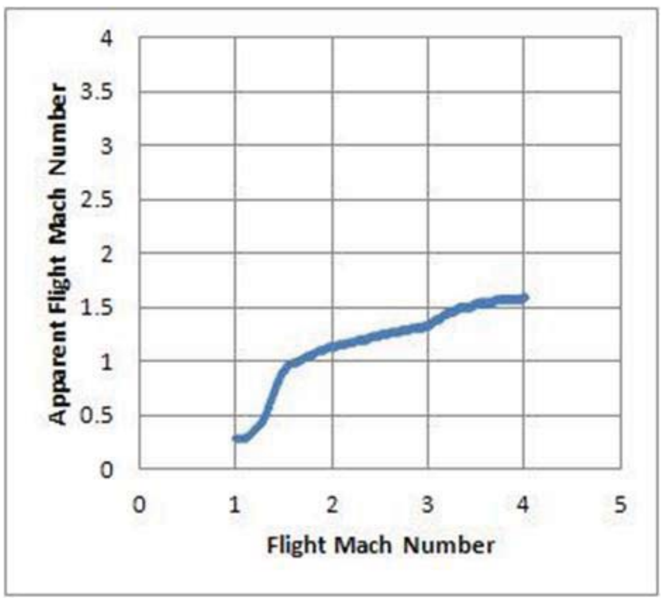


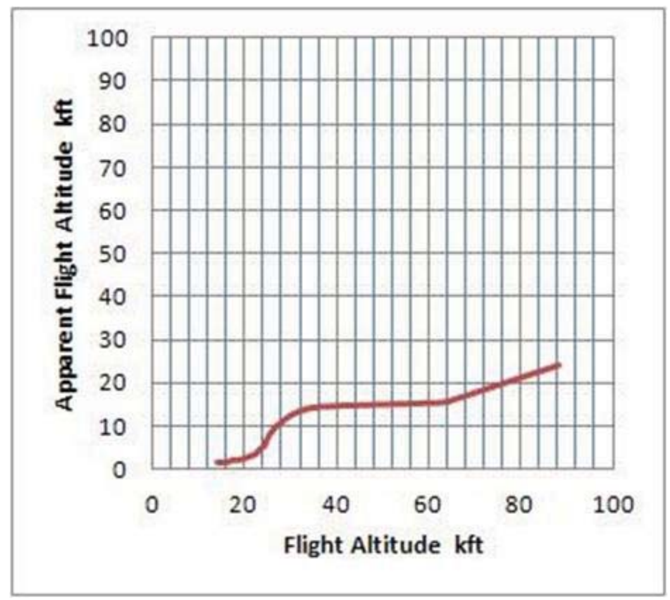
Reference: Stevenson, J. P., McDonnell Douglas F-15 Eagle, Aero Publishers, Fallbrook, California, 1978.

MIPCC technology: Apparent Mach and Apparent Altitude

RASCAL: Responsive Access Small Cargo Affordable Launch







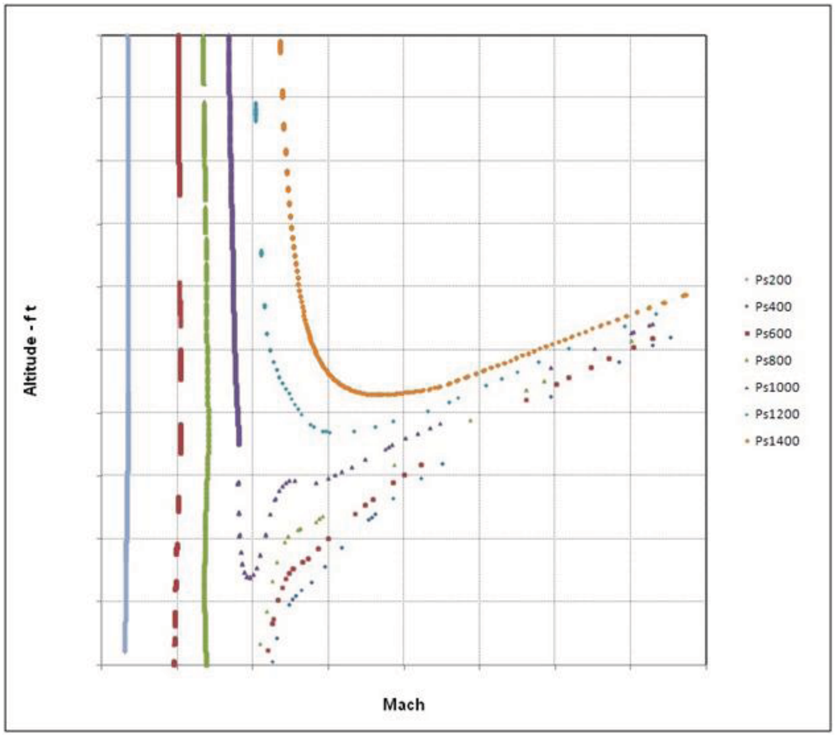
Mach 1.5 Conditions = Mach 4 Actual State

20kft Conditions = 80kft Actual State

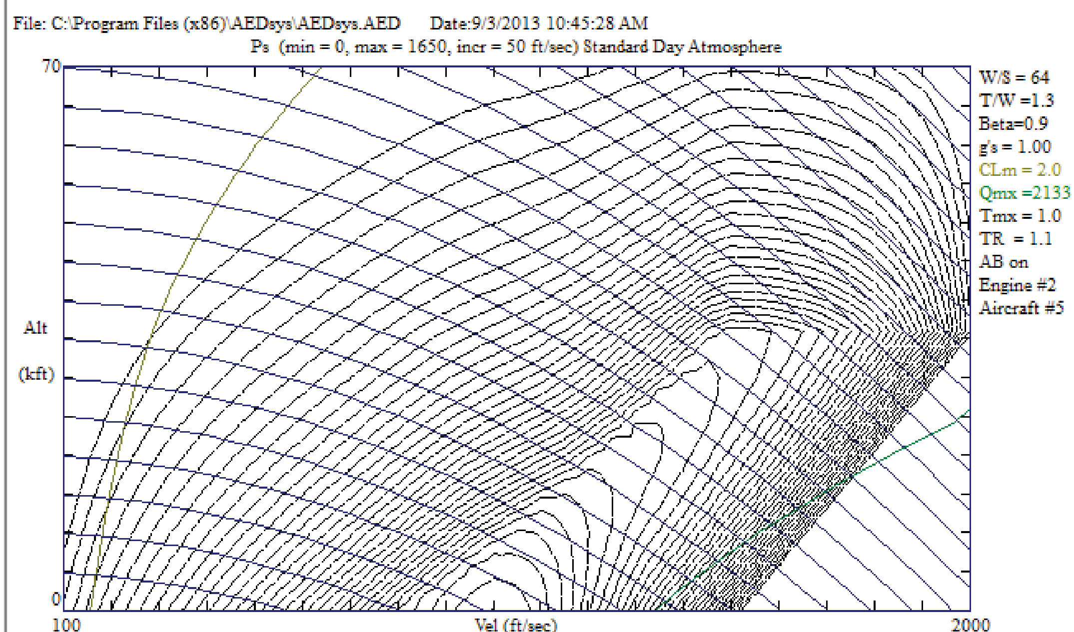
Source: Carter, P.H. and Balepin, V. V., "Mass Injection and Precompressor Cooling Engines Analyses," AIAA-2002-4127, 2002

All Rocket F-15

- Specific Excess Power (P_s) for rocket propulsion increases with altitude/Mach
- Typical Turbojet P_s decreases with altitude/Mach
- Generated with OTIS



All Rocket Excess Specific Power Contours

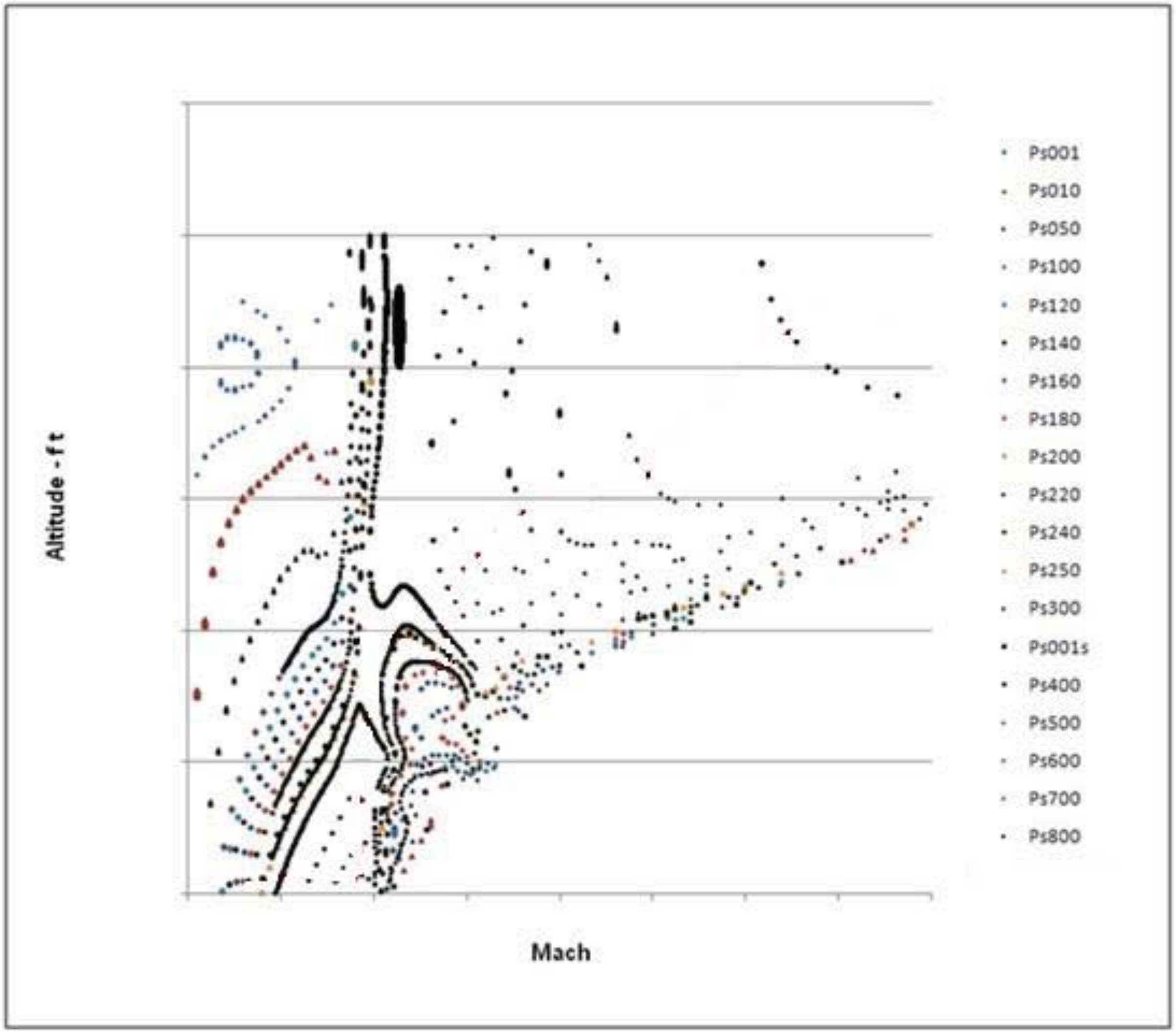


Typical Excess Specific Power Contours

Source: Mattingly, Aircraft Engine Design, 2002, ISBN 1-56347-538-3

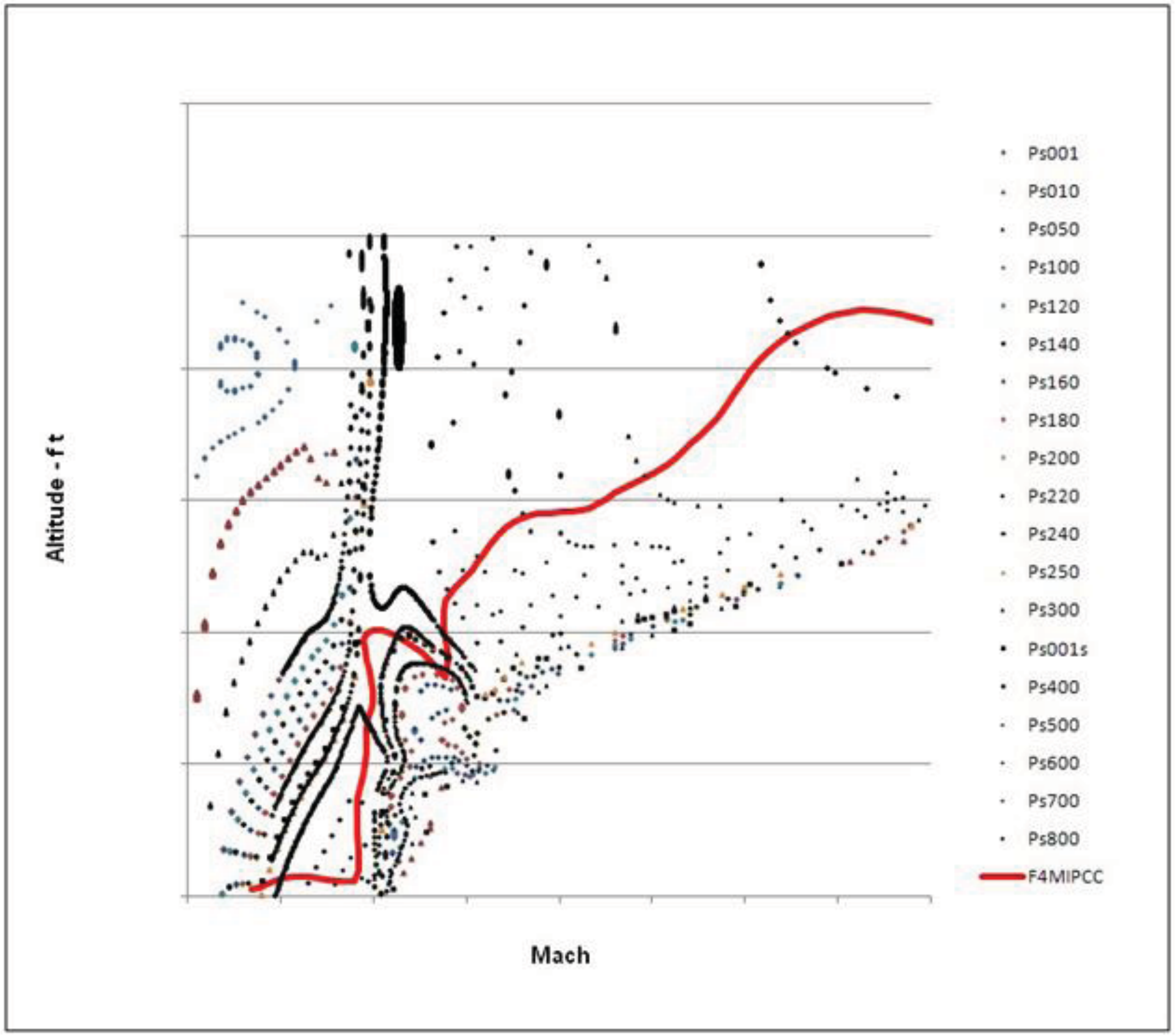
MIPCC Enhanced F-4 Phantom II

- **MIPCC F-4 excess power contours are similar in subsonic case, but morph into all rocket contours at higher altitudes/Mach**



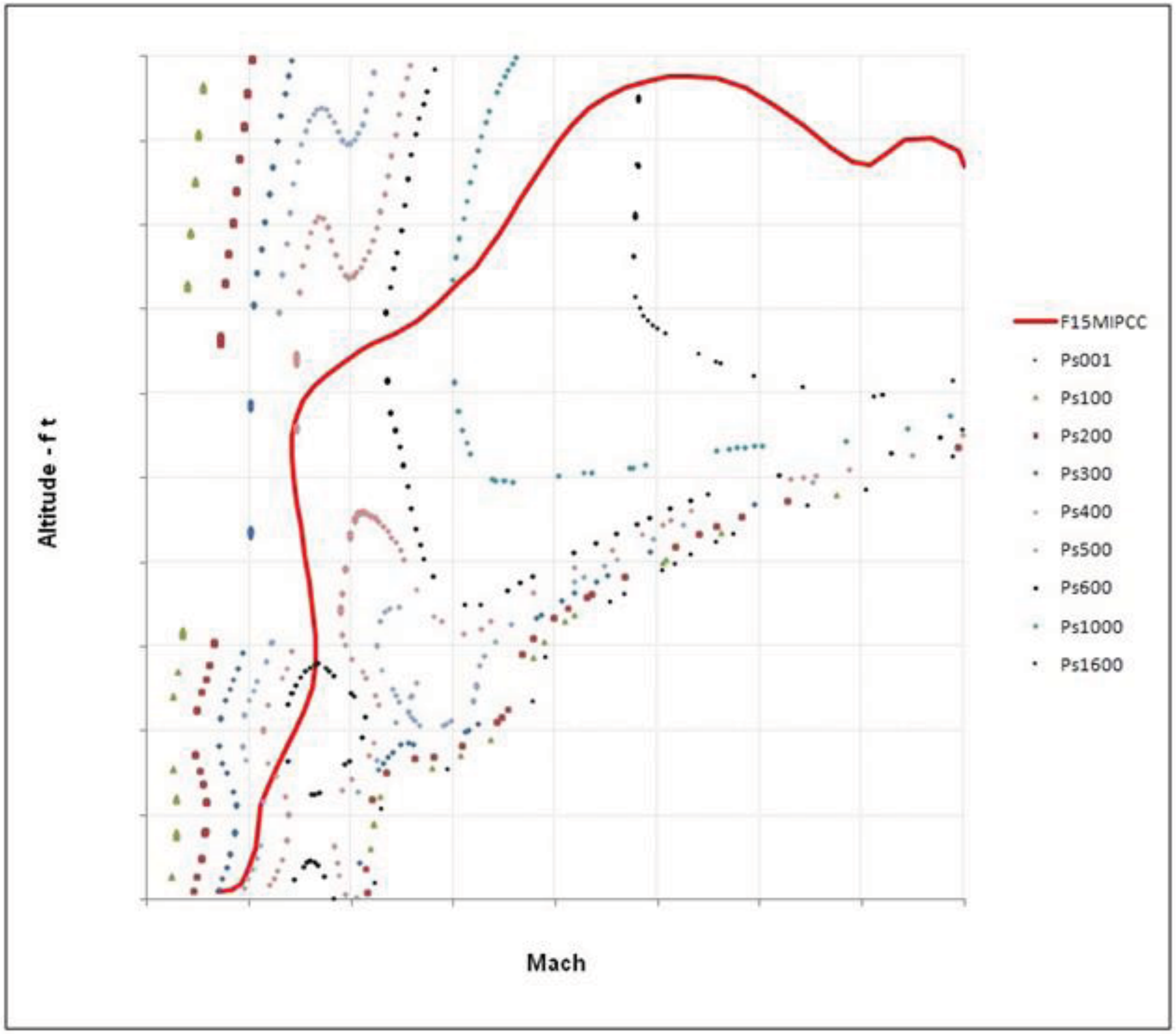
MIPCC Enhanced F-4 Phantom II

- **MIPCC F-4 minimum fuel climb has to execute transonic penetration dive**



MIPCC enhanced F-15

- **MIPCC F-15 minimum fuel climb - climbs sub-sonically above portion where drag makes a difference, and does not execute penetration dive**



Minimum Fuel Climb - Remaining Capacity

Specific energy of 274.66 Btu/lbm for clean configurations.

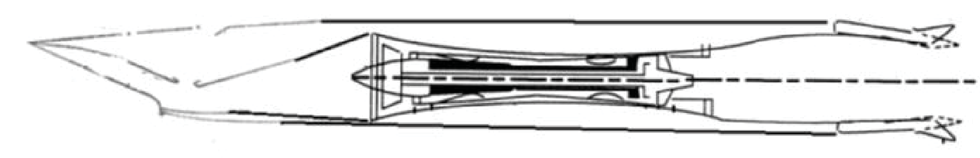
Description	F-4 MIPCC	F-15 MIPCC
Take-off Weight (lbm)	47,000	49,500
Remaining Fuel Capacity (lbm)	4,647	9,968

Specific energy of 420.01 Btu/lbm for clean configurations

Description	F-4 MIPCC	F-15 MIPCC
Take-off Weight (lbm)	47,000	49,500
Remaining Fuel Capacity (lbm)	1,356	8,616

Recommendations for Future Studies

- **Trajectory and performance**
  - **External rocket drag**
  - **MIPCC hardware aerodynamics shape**
- **Analytical and/or CFD analysis**
  - **Length of the relevant inlet system**
  - **Water and liquid oxygen droplet size**
  - **Phase change cooling.**
- **MIPCC effects**
  - **Inlet flow distortion**
  - **Lifetime of the compressor blades.**



Conclusions

- Preliminary comparison of MIPCC-enhanced F-4 and F-15:
- MIPCC-enhanced F-15 retains has more excess capacity
    - Reduced operational risk
- MIPCC-enhanced F-4 airplane has little excess
    - Exposure to programmatic risks
    - Replacement/Repair supply chain issues
- MIPCC enhancement economics-
    - New engine program could cost up to $1B? (Rand study)

Questions?

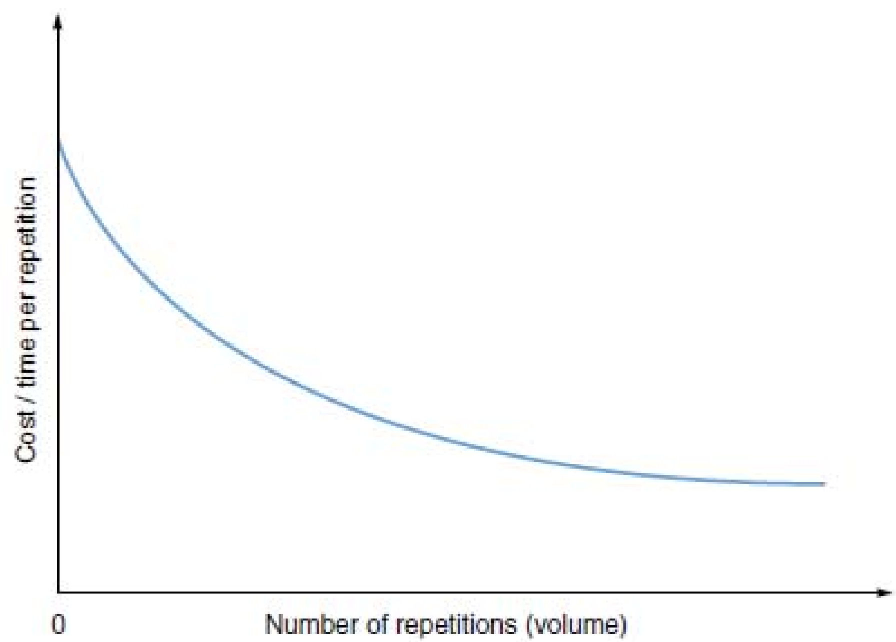
Background Slides

Outline

- Air Breathing Boost Stage
  - The mass production learning curve
- Air Launch Justifications
  - Power Levels - Rockets and Planes
  - System lifetime
  - NASA-Dryden Air Launch Efforts
- MIPCC F-4 & F-15
  - Simulation calibrations
  - Excess power contours
  - Remaining capacity
- Conclusions/Recommendations

Mass Production & The Learning Curve

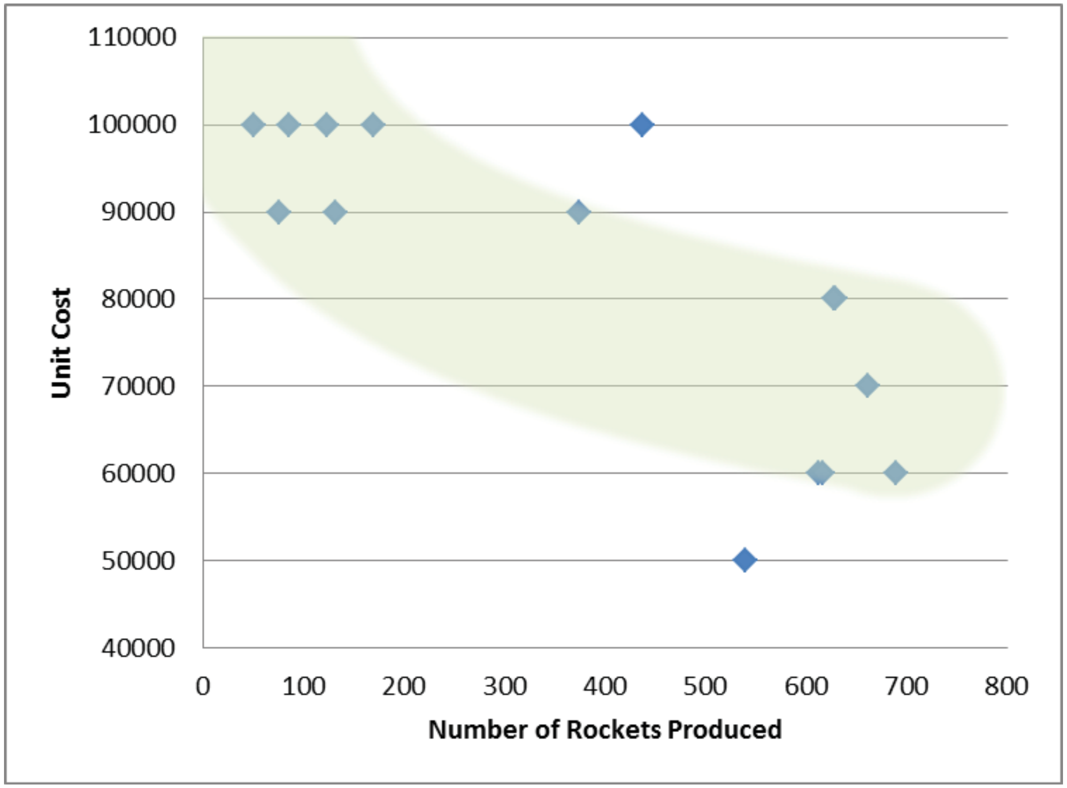
- **Production Costs - Operating Costs - Launch Costs**
  - **Mass production repetitions tend to reduce unit cost**



[1]T. P. Wright, "Factors Affecting the Cost of Airplanes," *Journal of the Aeronautical Sciences* (February 1936).

Pre-1950 Mass Production of Liquid Fueled Rockets

Historic evidence indicates mass production reduces rocket costs



Source: Smithsonian Institution Press #UG1282.G8K46 Year:1983

Launch Costs per Payload – Need for Larger Rockets?

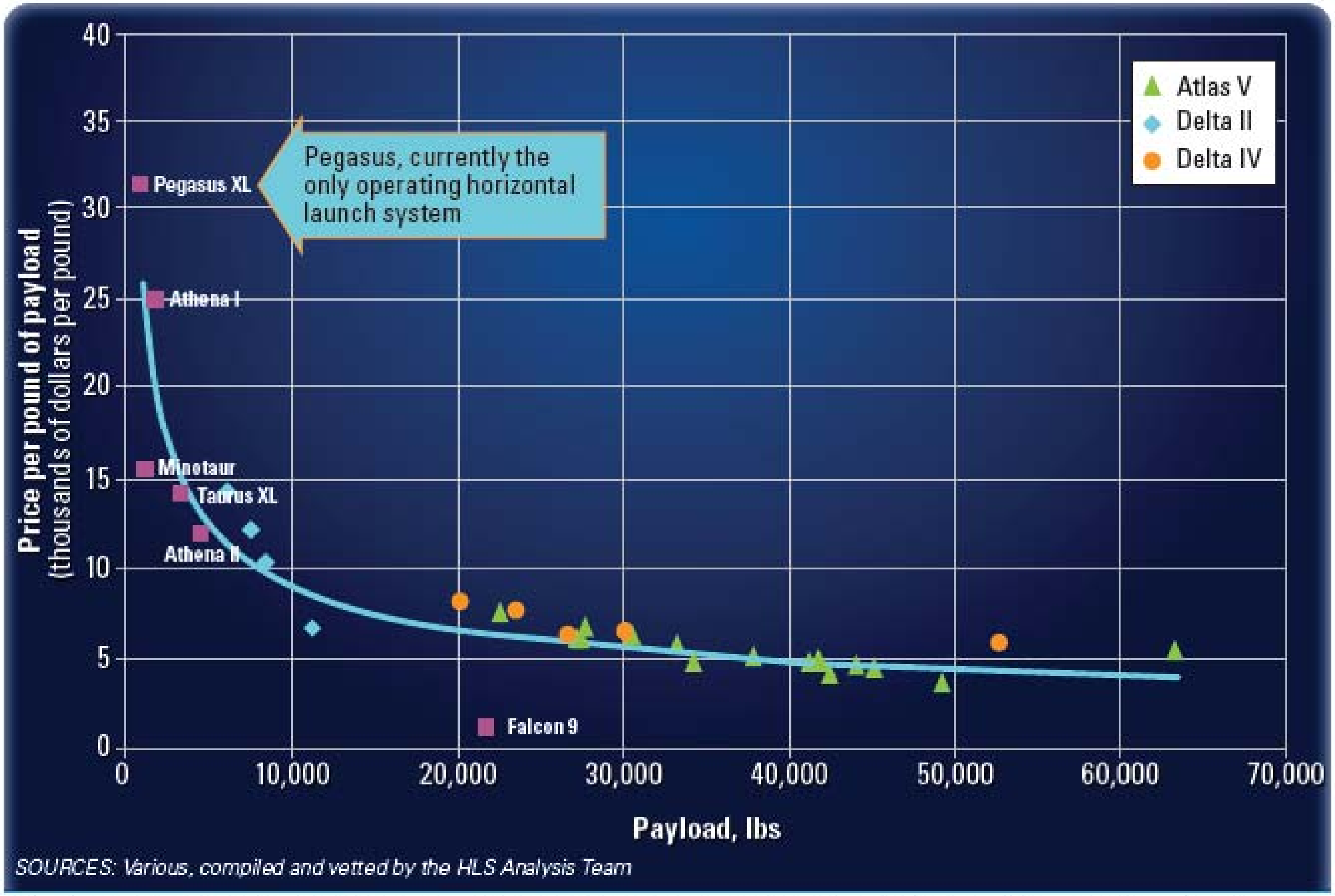


Figure 3 Price per pound of payload for existing U.S. launch vehicles. The price trend line is empirically fitted to existing price data.

Source: Report of the NASA-DARPA Horizontal Launch Study NASA SP 2011-215994

Power Levels - From Earth to Orbit

Review of Some Historic Launch Systems:

1.) Gemini III – 7200 lbs LEO, 87 X 121 nmiles, 32 d inc, 6 minutes to orbit

a.) First Stage Power Level – **50 Giga Watts**

b.) Stage Separation Conditions ~Mach 6.5 @ 200,000 feet

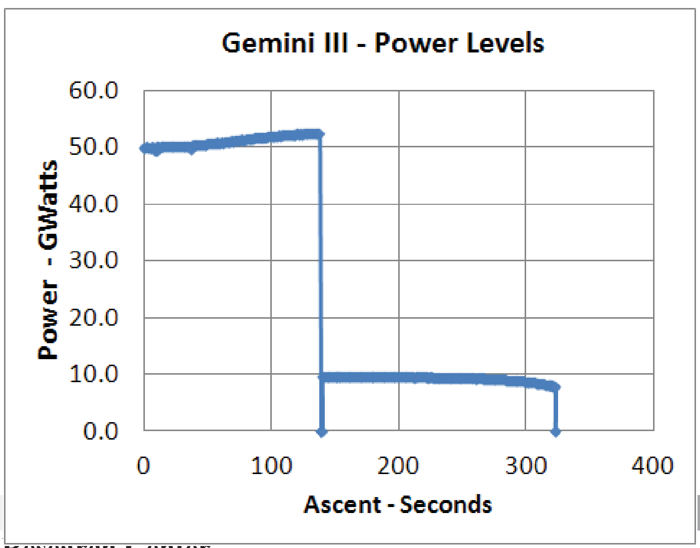
c.) Second Stage Power Level – **10 Giga Watts**

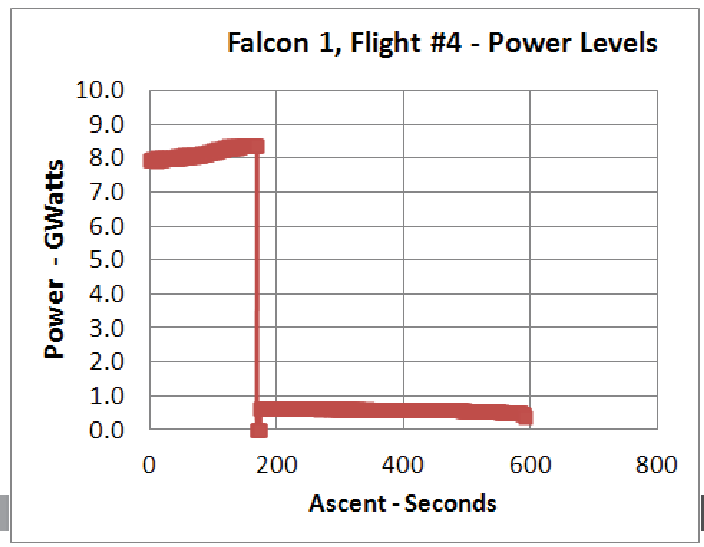
2.) Falcon 1, Flight #4 – 360 lbs LEO, 340 nmiles, 9d inc, 10 minutes to orbit

a.) First Stage Power Level – **8 Giga Watts**

b.) Stage Separation Conditions ~Mach 10 @ 310,000 feet

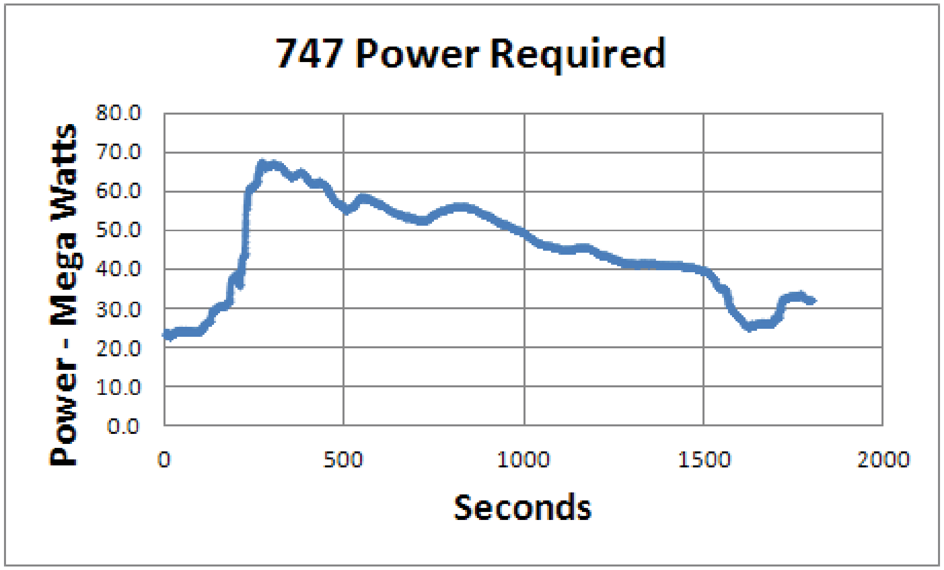
c.) Second Stage Power Level – **0.5 Giga Watts**

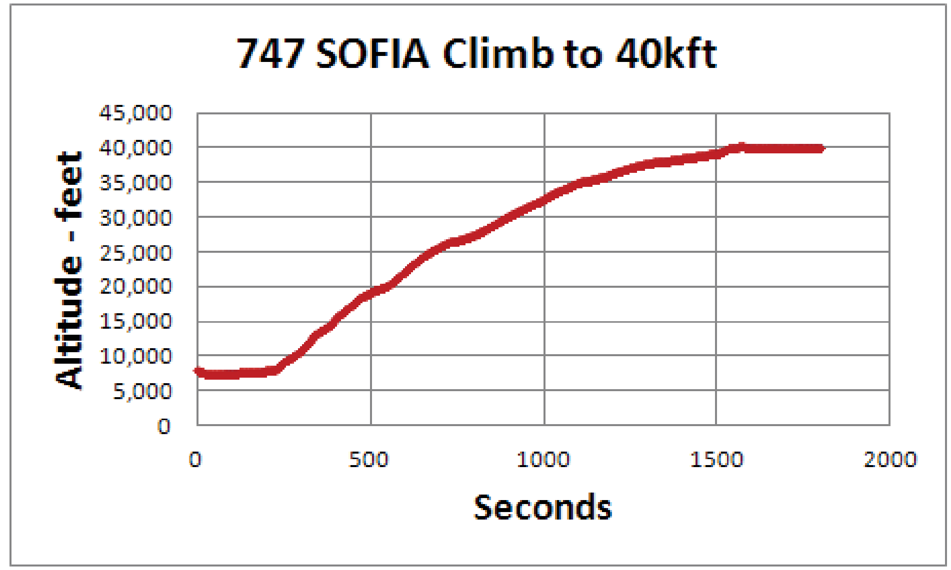




Comparison – 747 Climb to 40,000 feet

Let's examine the power required for a 747 to attain a gravitational potential energy state (height) of 40,000 feet and compare this to the power levels of the previous stated rocket systems.





747-SP SOFIA Climb data to 40,000 feet Mach 0.85 4 engines @ 50klbs thrust STP, Initial weight was 512,000 lbs, and the final weight was 497,000 lbs, time to climb ~16 minutes