Solar Based Propulsion System UAV Conceptual Design (*)

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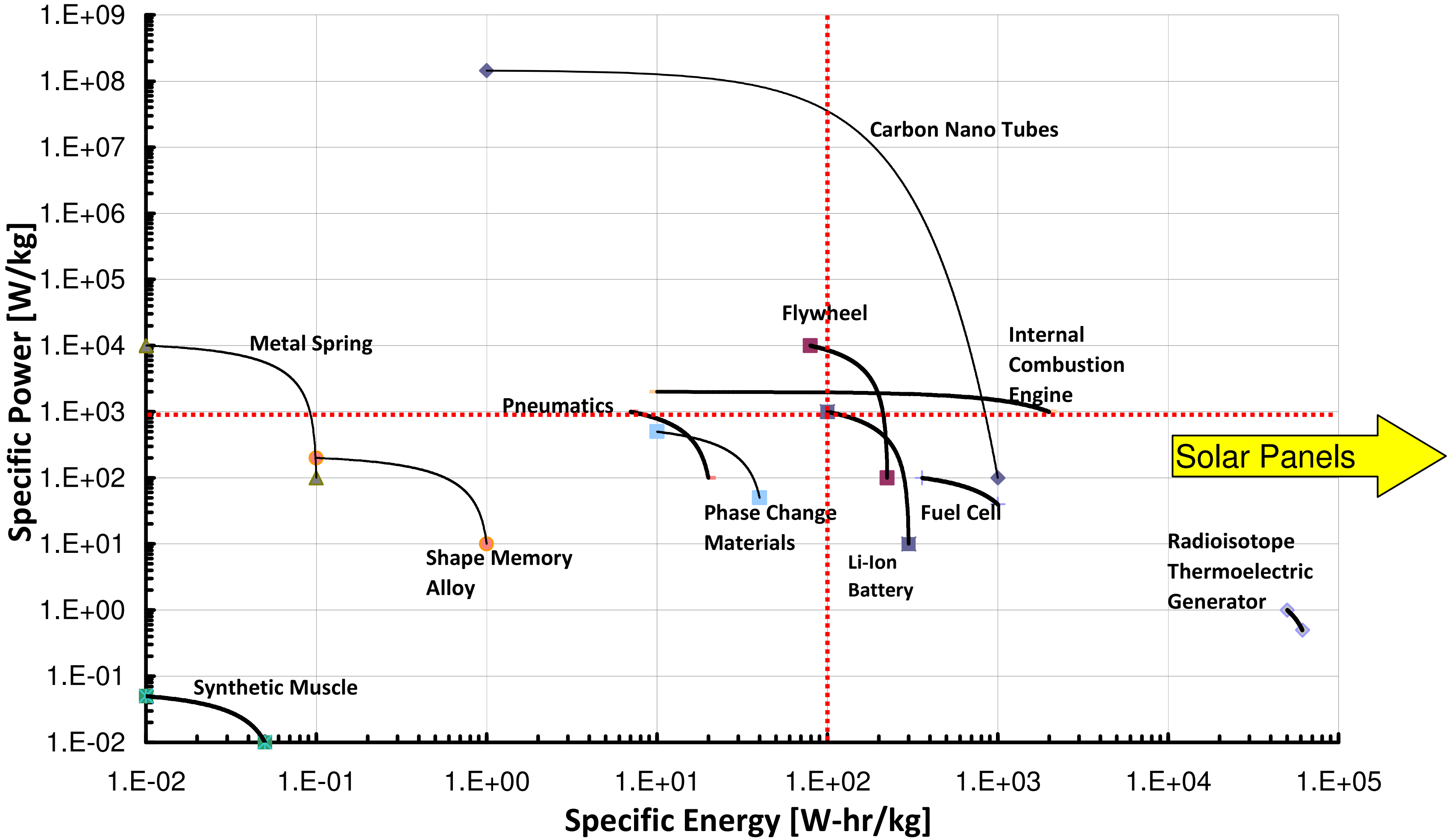
(*)Ayele A., Gur O., Rosen A., "Conceptual MDO of solar powered UAV," *53rd Israel Annual Conference on Aerospace Sciences,* March 6-7, 2013, Israel

3rd Conference on Propulsion Technologies for Unmanned Aerial Vehicles
January 30, 2014, Technion, Haifa, Israel

Ragone Chart

Curtsey of Lidor A., Weihs D., Sher E.



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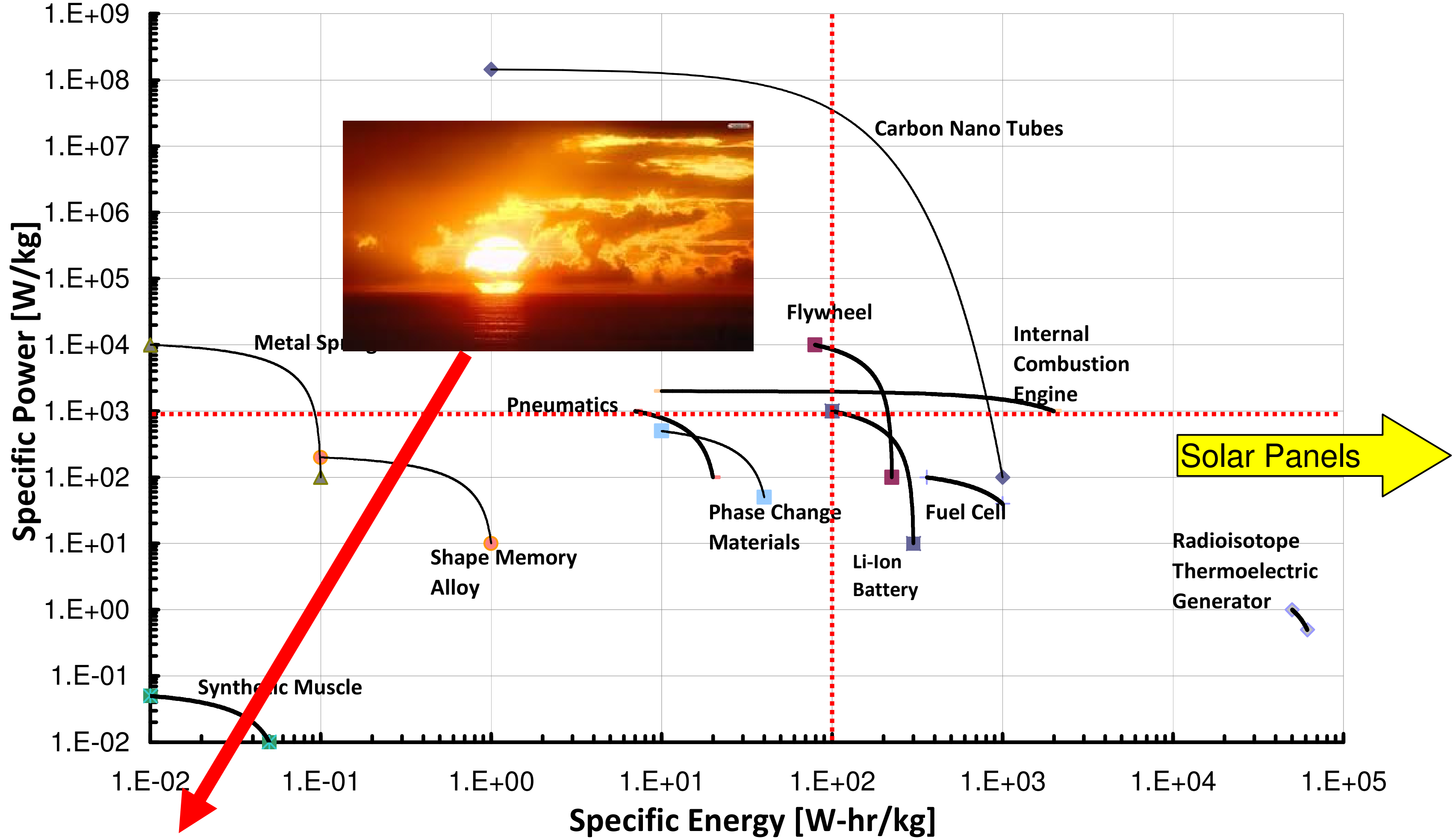

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Firsts Steps

1st "Solar" Vehicle
Sunrise II, Nov. 1975

1st Manned "Solar" Vehicle
Solar Riser, April 1979

1st Manned Solar Vehicle
Gossamer Pinguin, May 1980

Crossing the English Channel
Solar Challenger, July 1981

Endurance Record, 2 Weeks Flight
Qinetiq Zephyr, July 2010

André Noth, "History of Solar Flight," Autonomous System Lab, Swiss Federal Institute of Technology, Zürich, July 2008

NASA HALEs (High Altitude, Long Endurance)

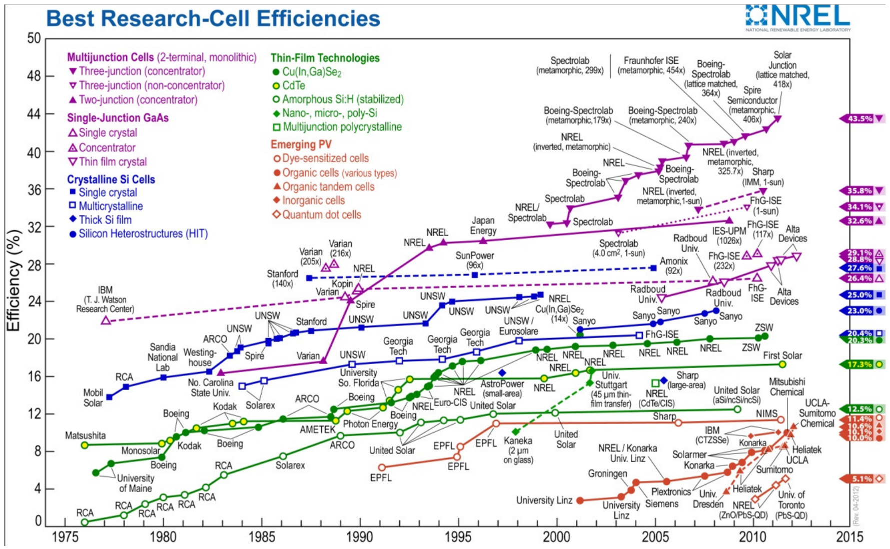


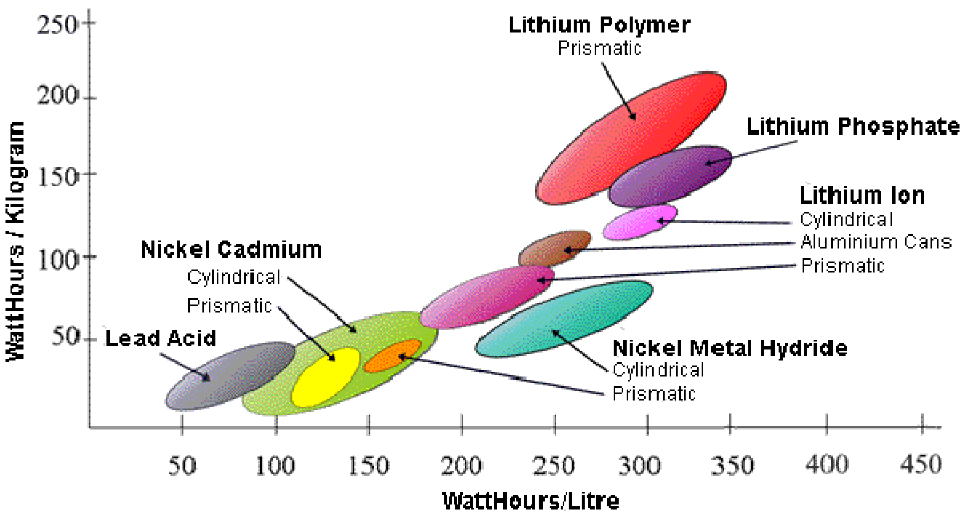

Pathfinder	Pathfinder-Plus	Centurion	Helios
1994-1998	1998-2002	1997-1999	1999-2003
70,500 ft, 1998	80,200 ft, 1998	80,000 ft (goal)	96,800 ft, 2001
b = 30m	b = 37m	b=63m	b=75m
AR=12	AR=15	AR=26	AR=31
m=250 kg	m=315 kg	m=860kg	m=930kg

Dryden Flight Research Center Website, www.nasa.gov [cited: February 2013)

Main Design Challenge

- **Energy Balance**
  - **Solar Panels Efficiency**
  - **Energy Storage Weight / Volume**
- Aerodynamics
- Structure (Weight)





Main Design Challenge

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  - **Energy Storage Weight / Volume**
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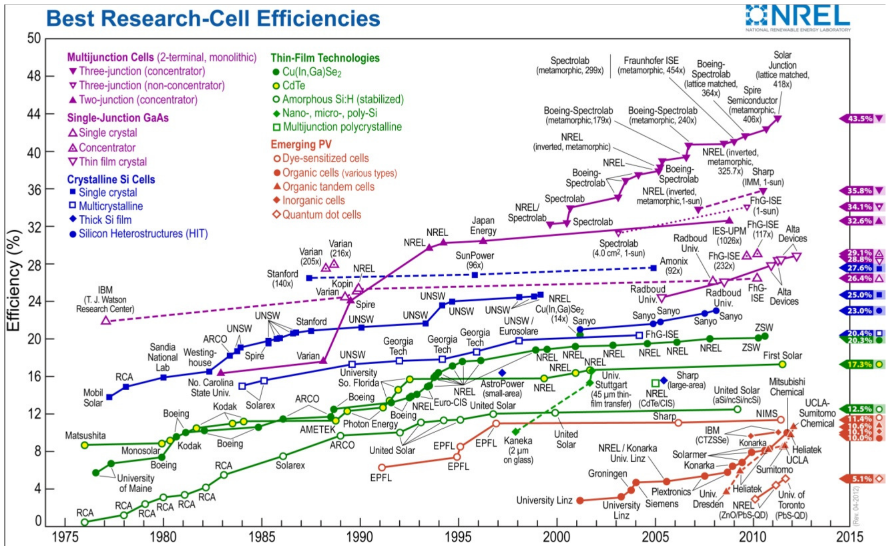
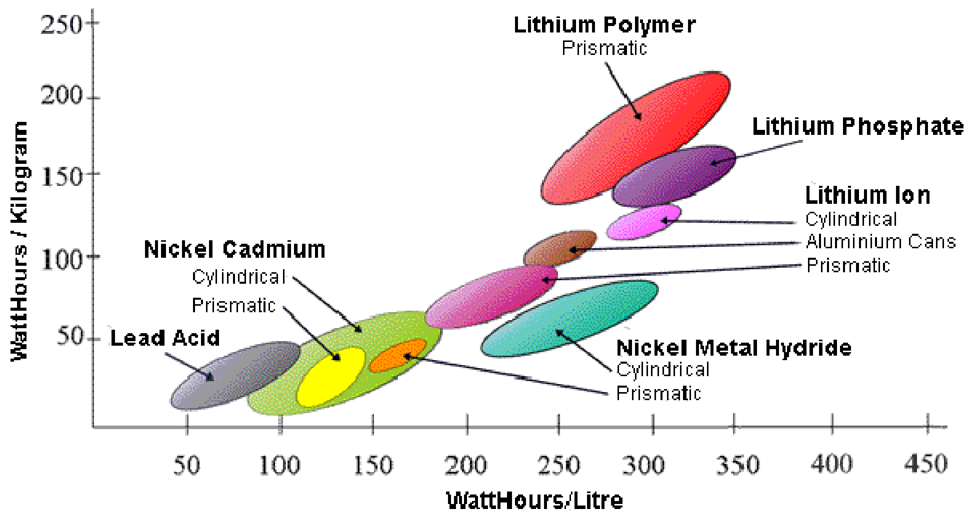
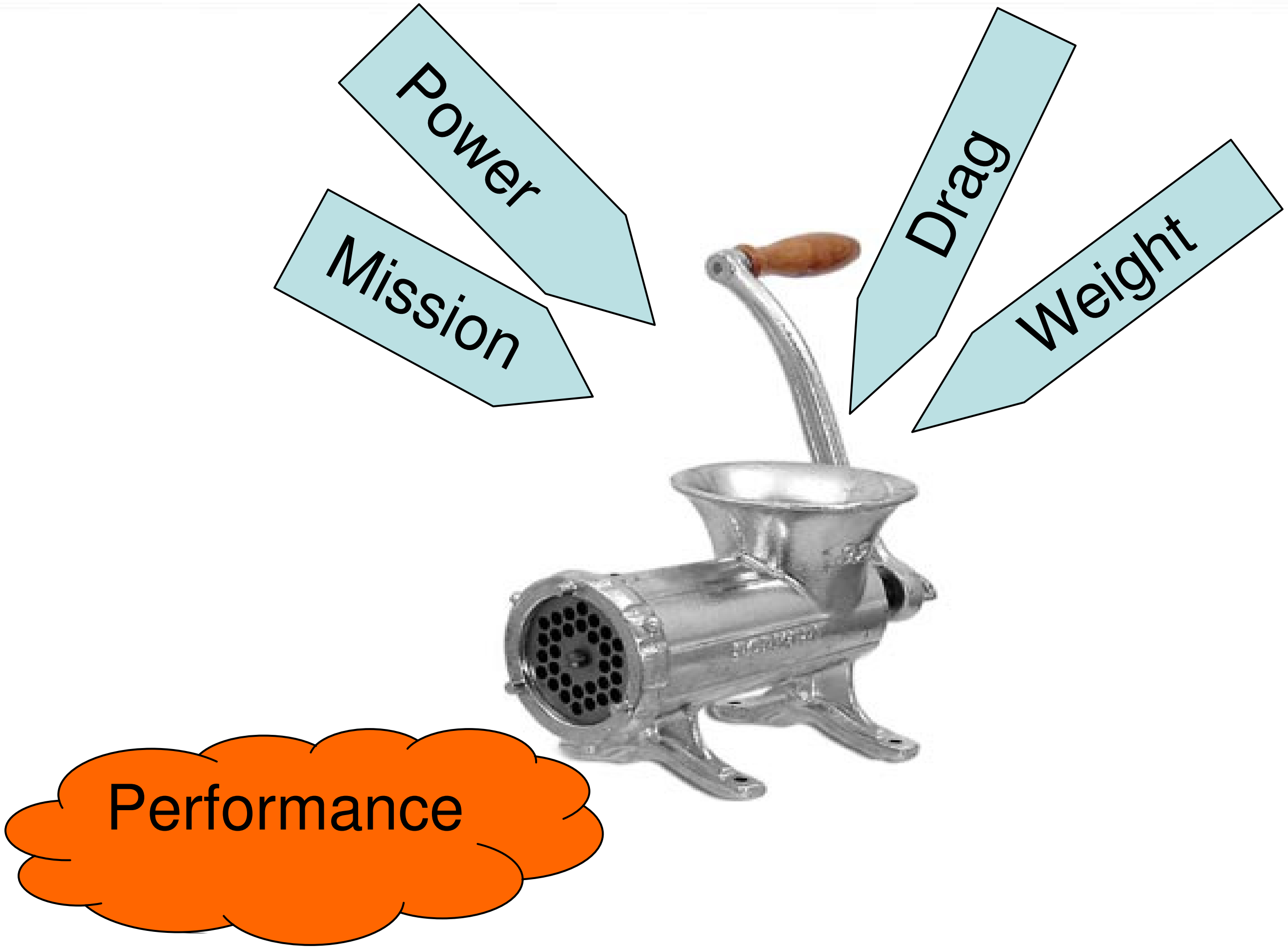
- Structure (Weight)

Solution → MDO: Multidisciplinary Design Optimization



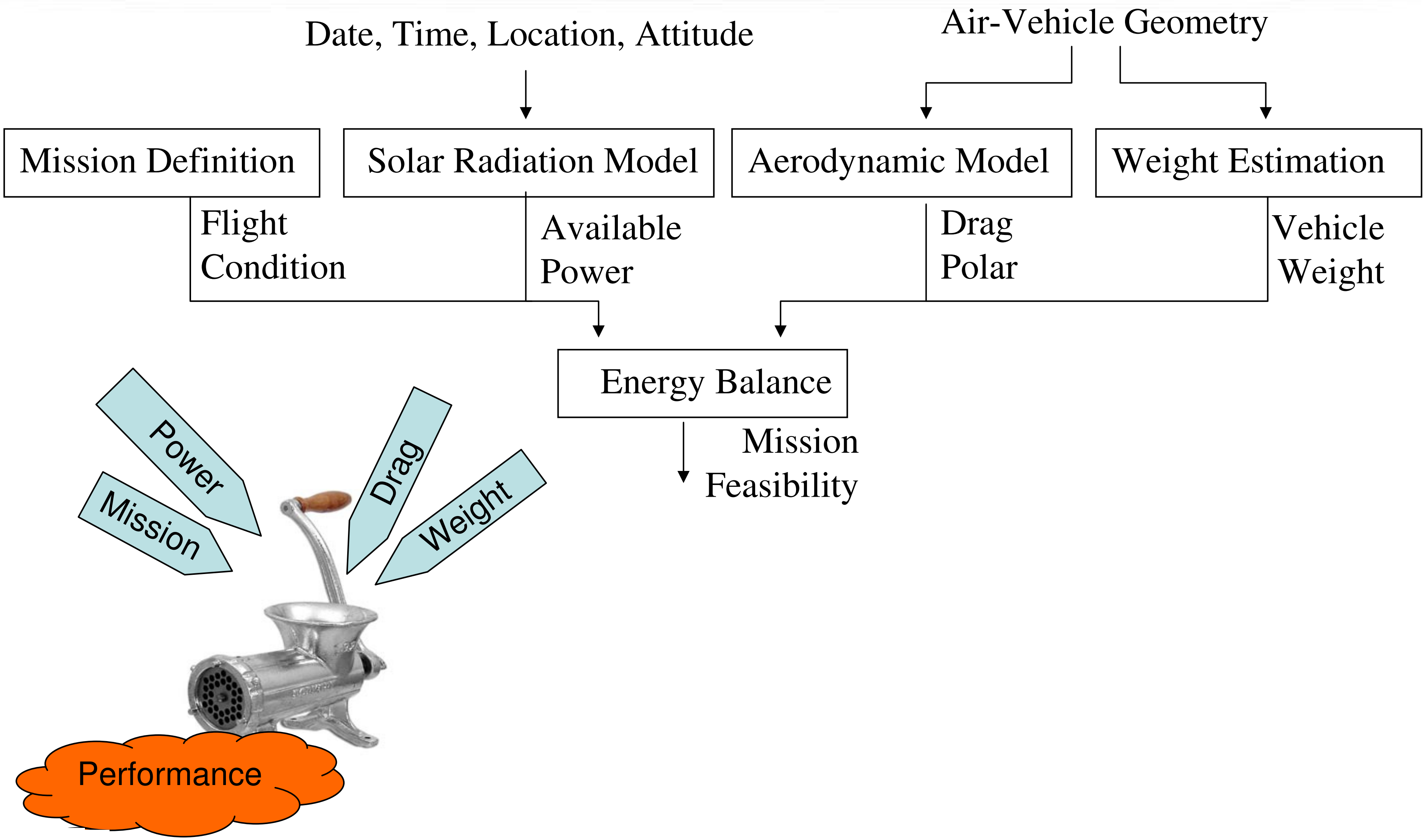


Performance, Like Sausages…



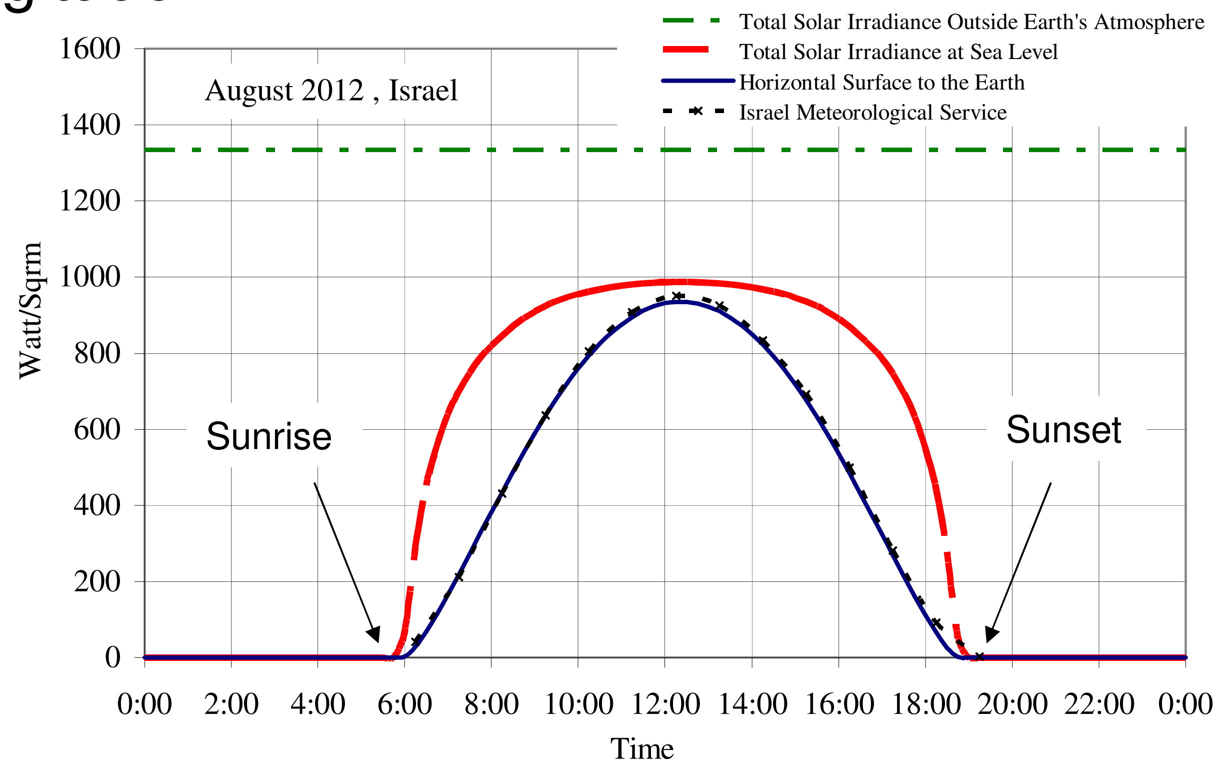
Laws, like sausages, cease to inspire respect in proportion as we know how they are made
(John Godfrey Saxe, 1869)

Analysis Model



Solar Radiation Model

- **Based on ESDU formulation**
  - Time (date / hour)
  - Latitude / Longitude
  - Altitude
  - Attitude



Engineering Sheet Data Units, "Solar heating: total direct irradiance within the earth's atmosphere," ESDU 69015, September 1975

Aerodynamic Drag Estimation

- Lift dependent drag
  - Only induced
  - Simple Oswald factor (e = 0.9)

$$C_D = C_{D0} + \frac{1}{\pi AR\,e} C_L{}^2$$

- Zero lift drag
  - Drag bookkeeping
  - Form-Factor
  - Interference-Factor

$$C_{D0-i} = C_{f-i} FF_i IF_i \frac{S_{Wet-i}}{S}$$

Wing

$$FF_{i,Wing} = 1. + 1.44\frac{t}{c} + 2\left(\frac{t}{c}\right)^2$$

$$IF_{i,Wing} = 1.1$$

Fuselage

$$FF_{i,Fuse.} = 1 + \frac{60}{\left(L_{Fuse.}/\sqrt{W_{Fuse.}H_{Fuse.}}\right)^2} + 0.0025\frac{L_{Fuse.}}{\sqrt{W_{Fuse.}H_{Fuse.}}}$$

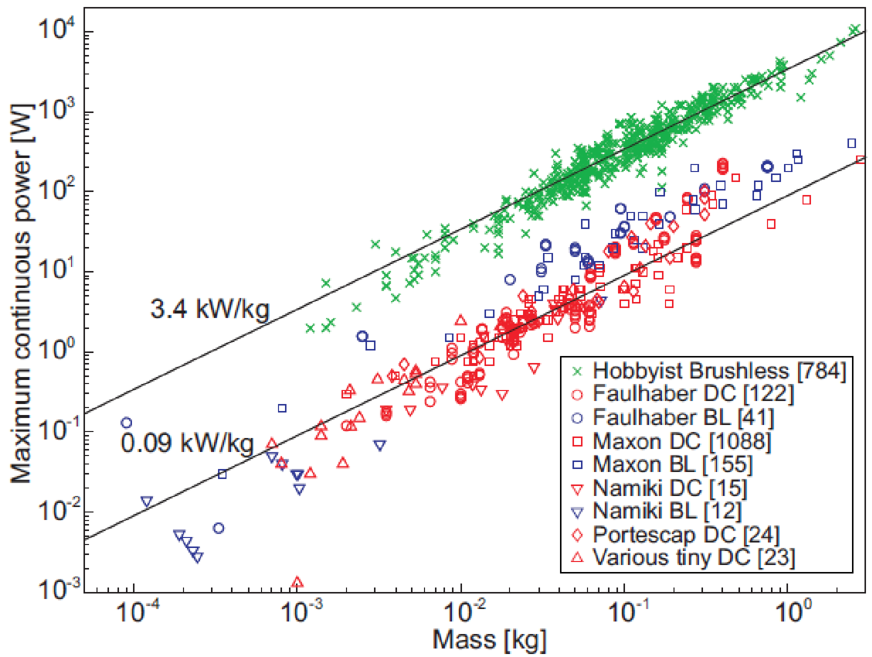
$$IF_{i,Fuse.} = 1$$

Roy T. Schemensky, “Development of an empirically based computer program to predict the aerodynamics characteristics of aircraft. Volume 1, Empirical methods,” Air Force Flight Dynamic Laboratory, AD-780-100, November 1973

Weight Estimation

- Weight Bookkeeping
  - Structure
  - Propulsion system
  - Batteries
  - Solar Panel
  - Payload

Motor Weight Estimation



A. Noth, "Design of Solar Powered Airplanes for Continuous Flight," Ph.D. Thesis, ETH, Eidgenössische Technische Hochschule Zürich, September 2008

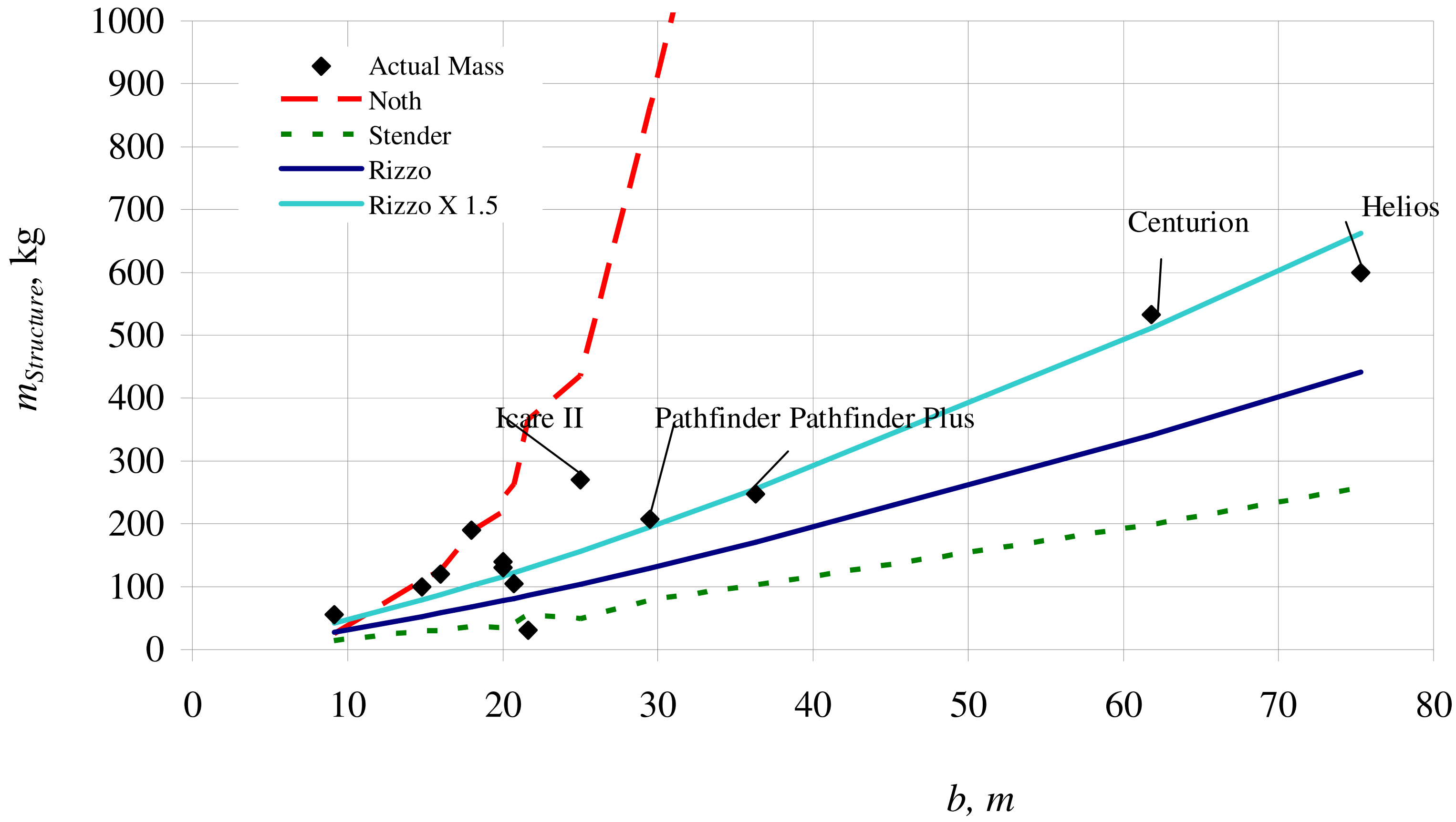
Structure Weight Estimation

$$m_{Structure,Noth} = 0.44b^{3.1}AR^{-0.25}$$

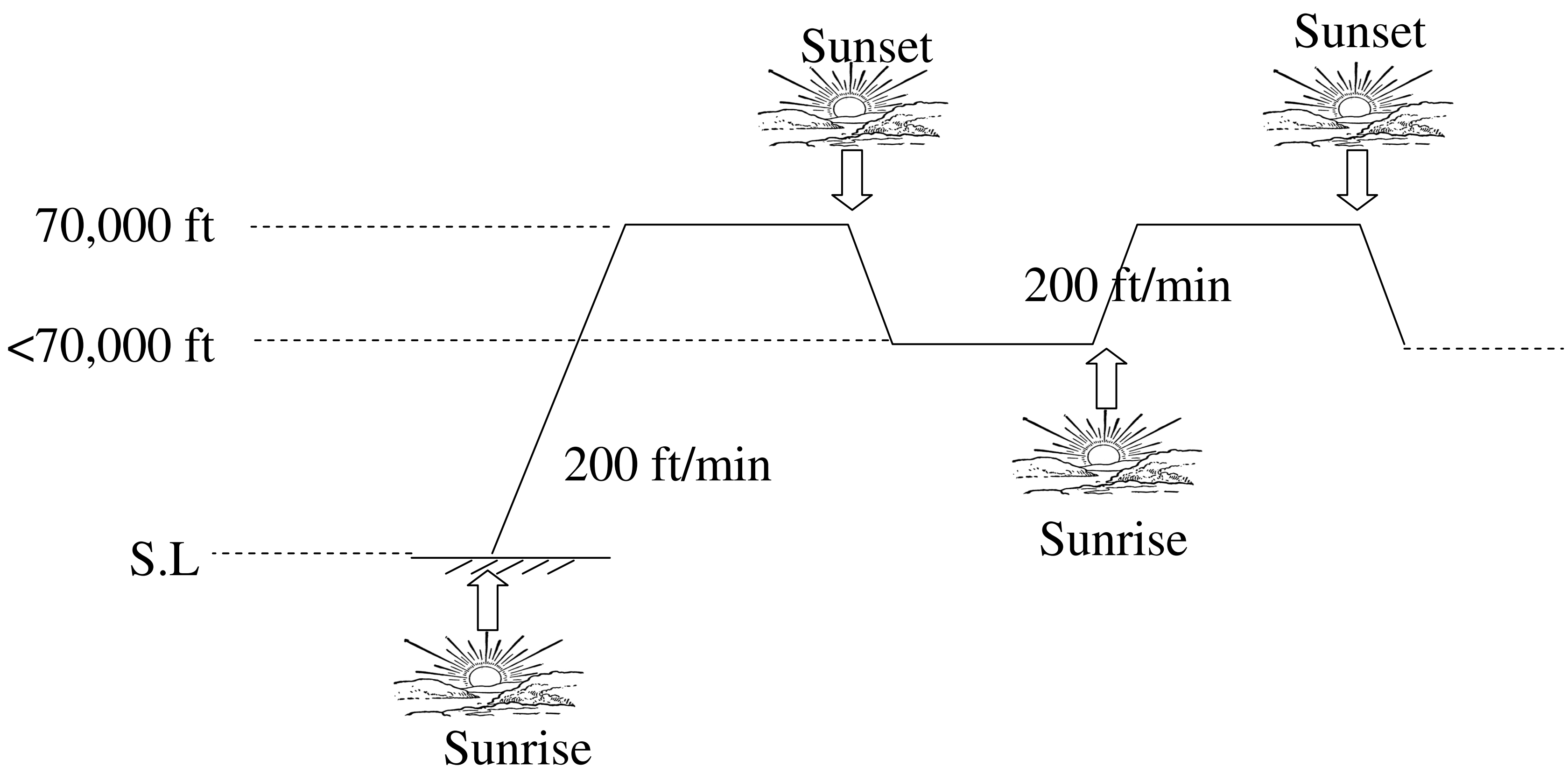
$$m_{Structure,Rizzo} = 15.19b^{1.312}AR^{-0.005}$$

$$1.5 \times m_{Structure,Rizzo} = 22.8b^{1.312}AR^{-0.005}$$

$$m_{Structure,Stender} = 8.763b^{1.556}AR^{-0.311}$$



Mission Definition



Mathematical Programming Formulation

$$\min_{\mathbf{x}\in\Re^n} \mathbf{f}(\mathbf{x})$$

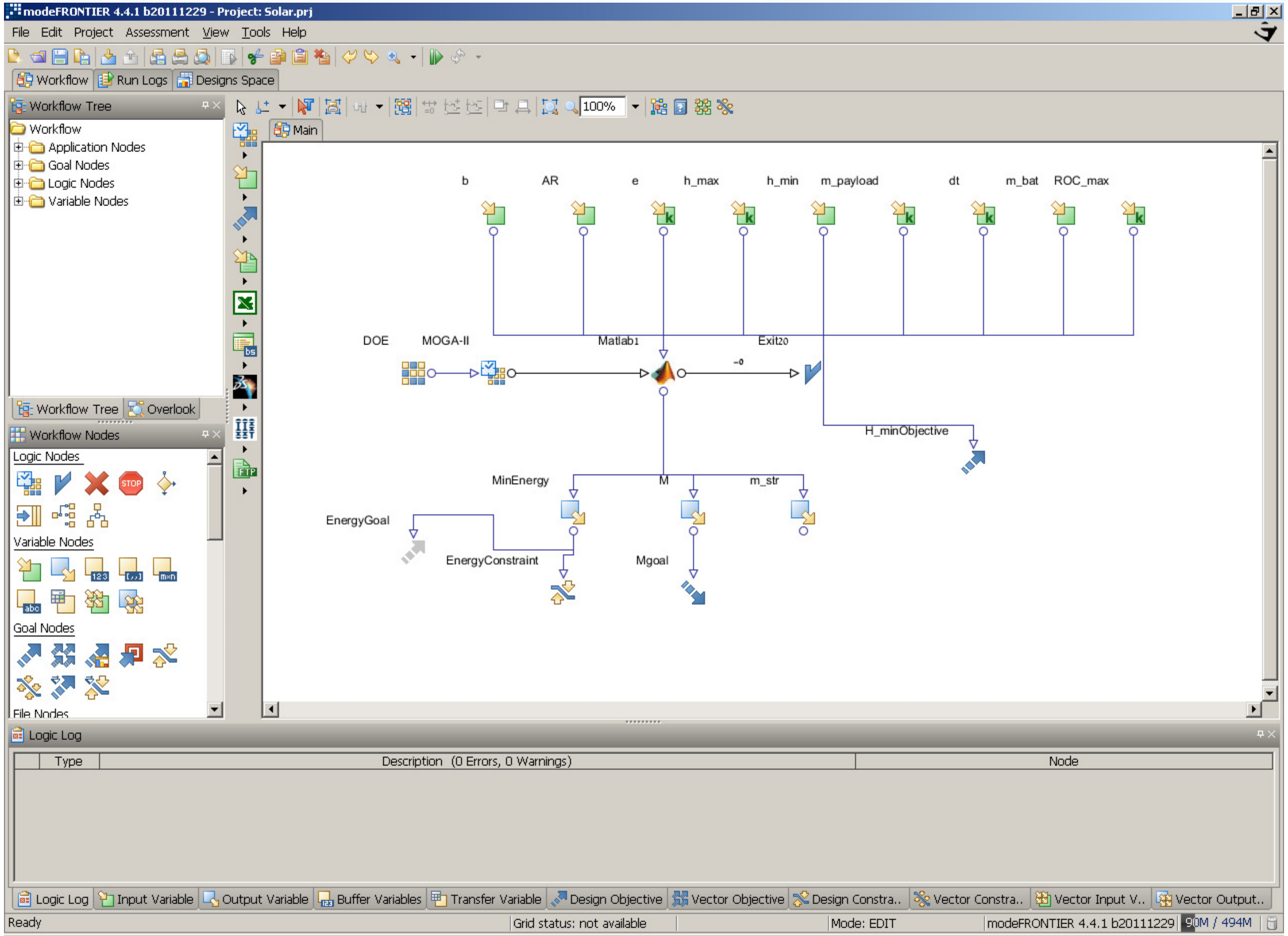
$$s.t.$$

$$\mathbf{g}(\mathbf{x}) \le 0$$

- $\mathbf{f}(\mathbf{x})$ – cost function
  - Vehicle mass
  - Night time altitude
  - Payload mass
- $\mathbf{x}$ – design variables
  - Wing dimension
  - Battery mass
- $g(\mathbf{x})$ – design constraints
  - Energy balance

Numerical Implementation

Matlab & ESTECO modeFrontier environment



Design Case A

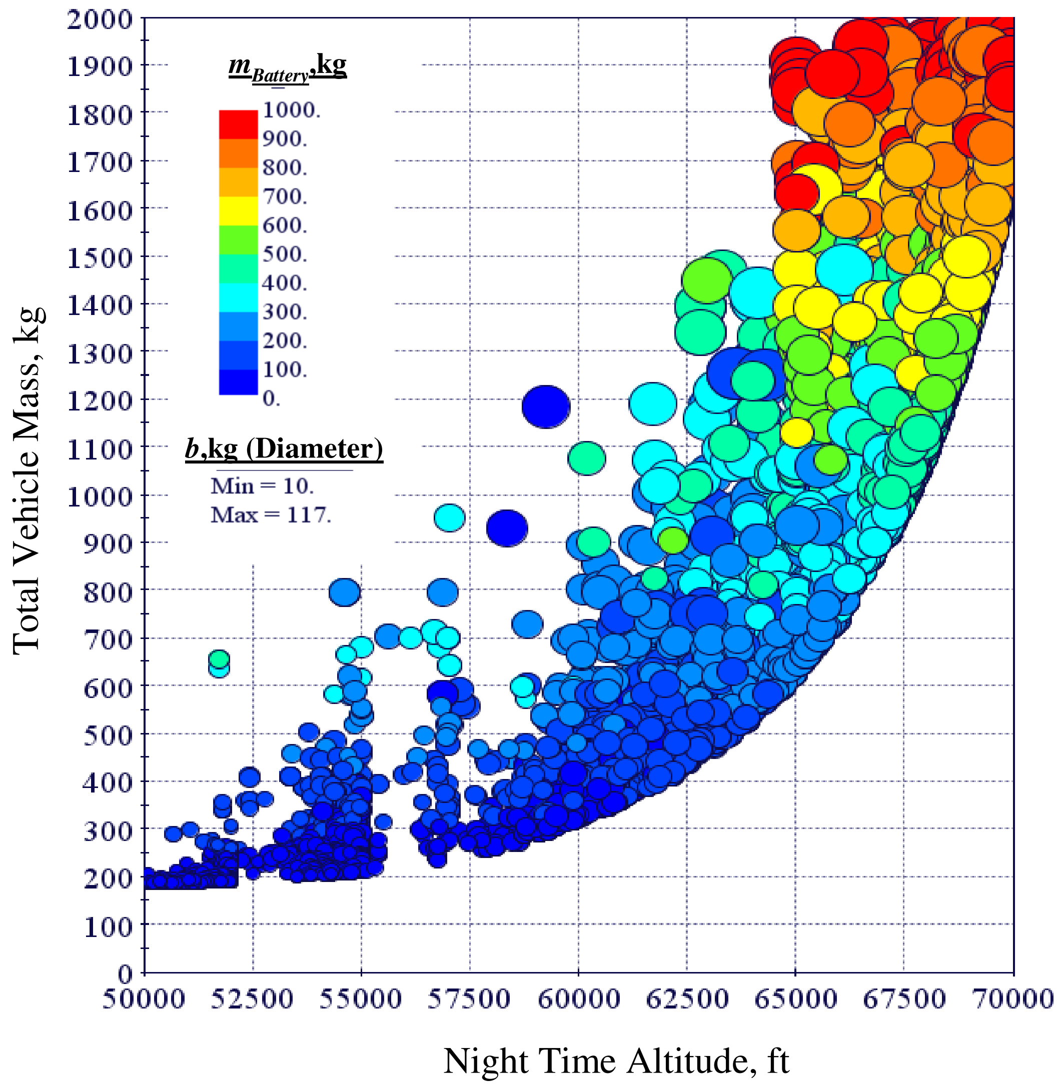
- Design Variables

Design Variable	Minimum Value	Maximum Value
Battery mass, $m_{Battery}$	10 kg	1000 kg
Minimum Cruise Altitude	50,000 ft	70,000 ft
Aspect Ratio, AR	5	40
Wing Span, b	10 m	100 m

- Cost Function
  - Night Time Altitude - Maximize
  - Total Vehicle Mass - Minimize
- Design Constraint
  - Energy balance

Design Case A, Pareto Front

$m_{Payload} = 2$ kg



Design Case A, Pareto Front

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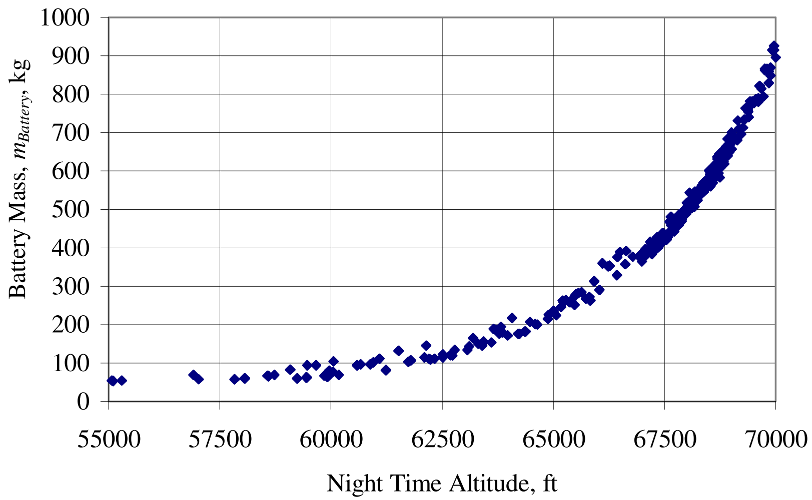
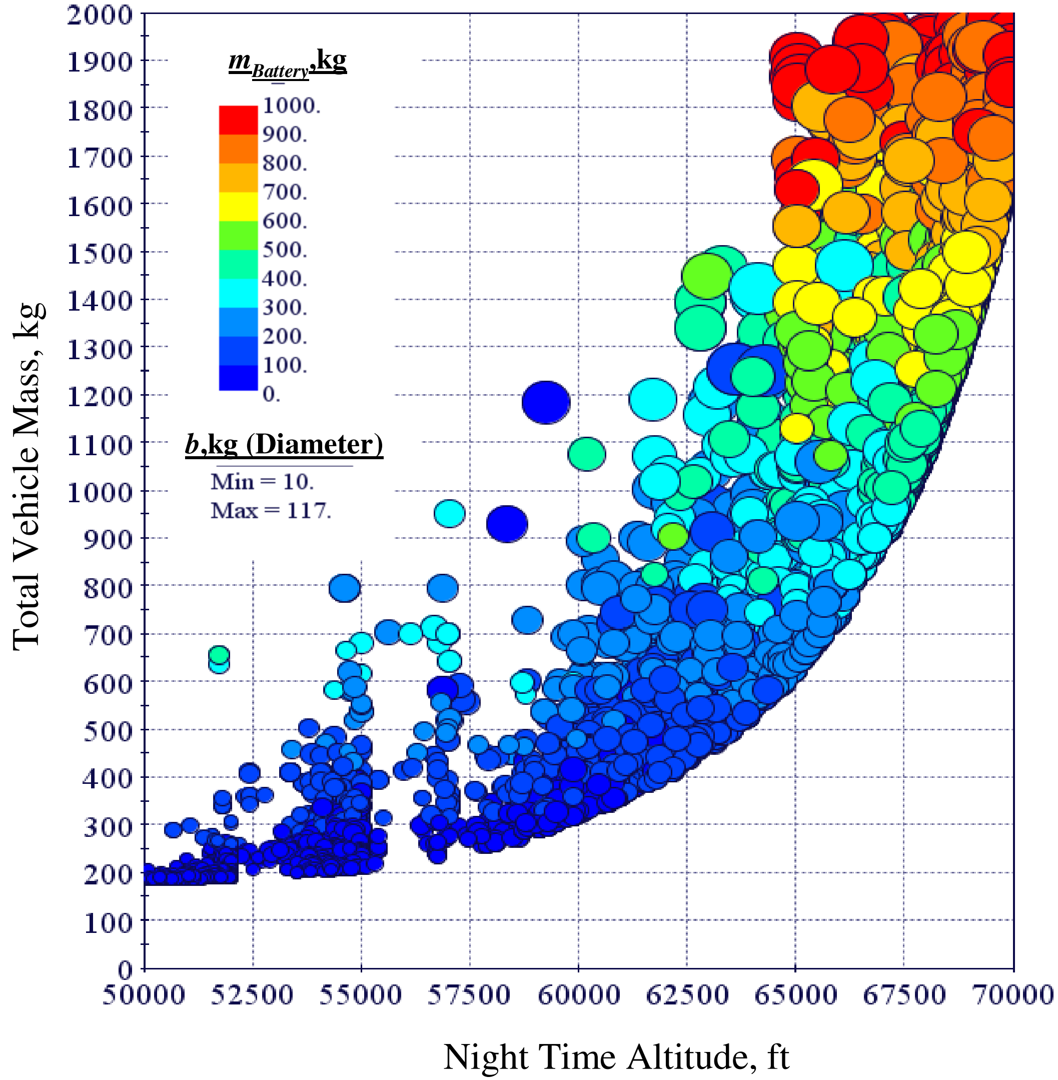
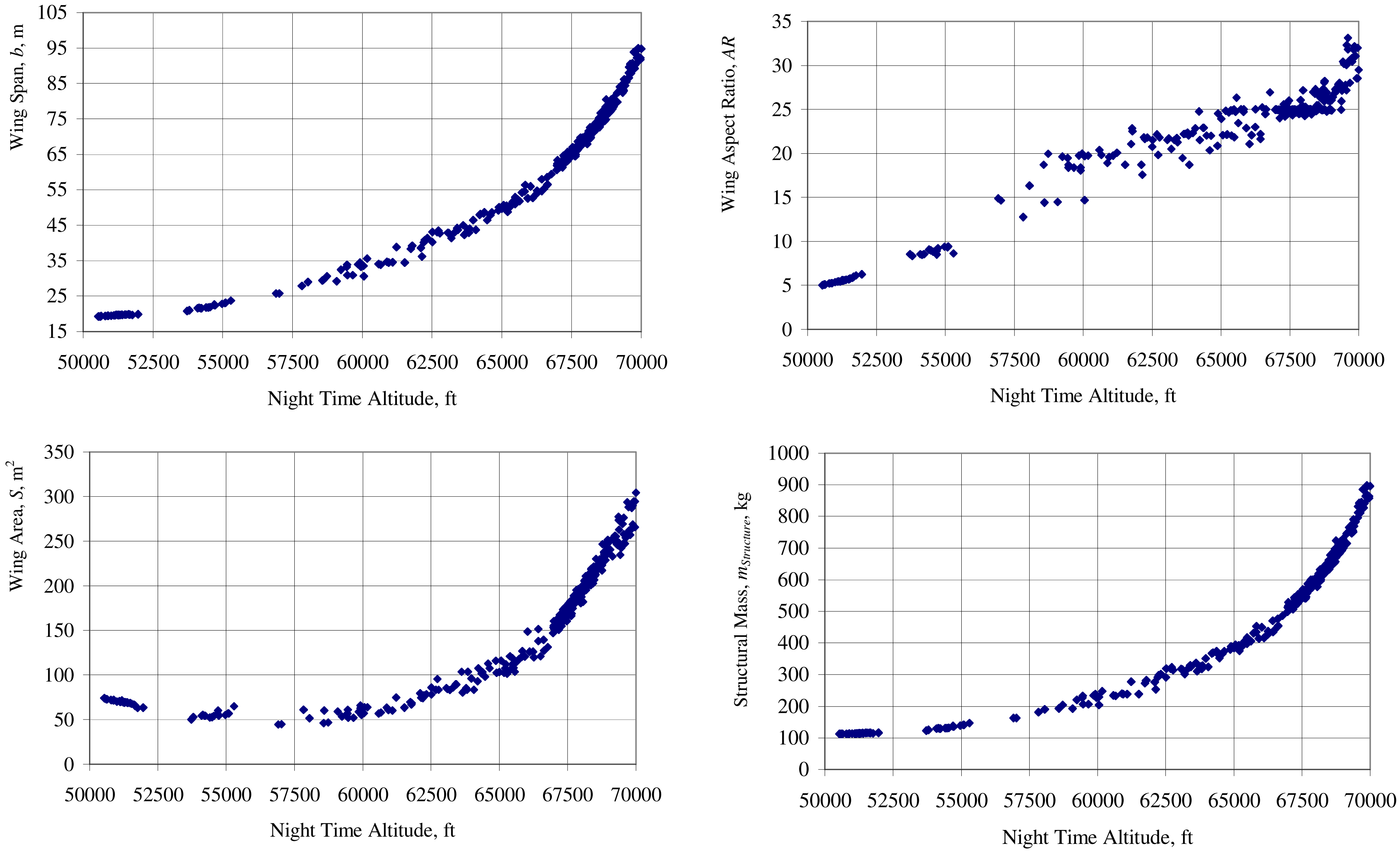




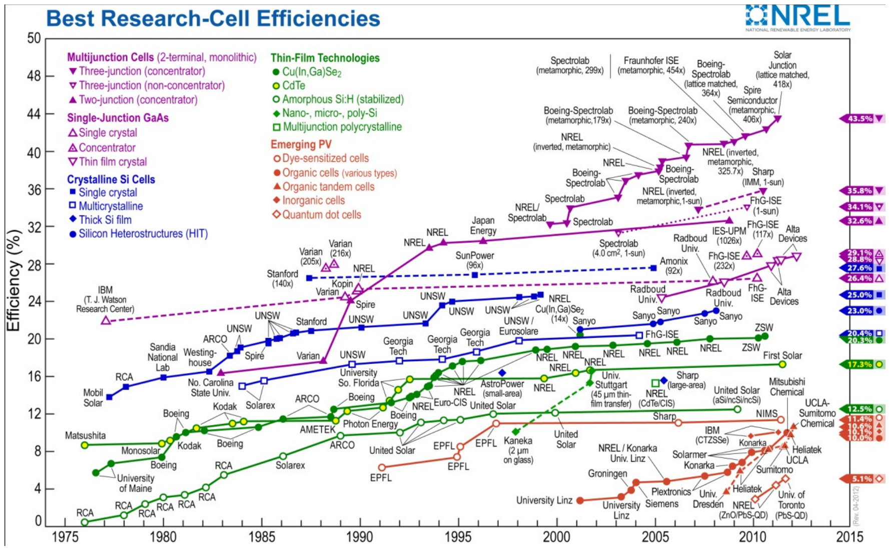
Design Case A, Pareto Front Designs

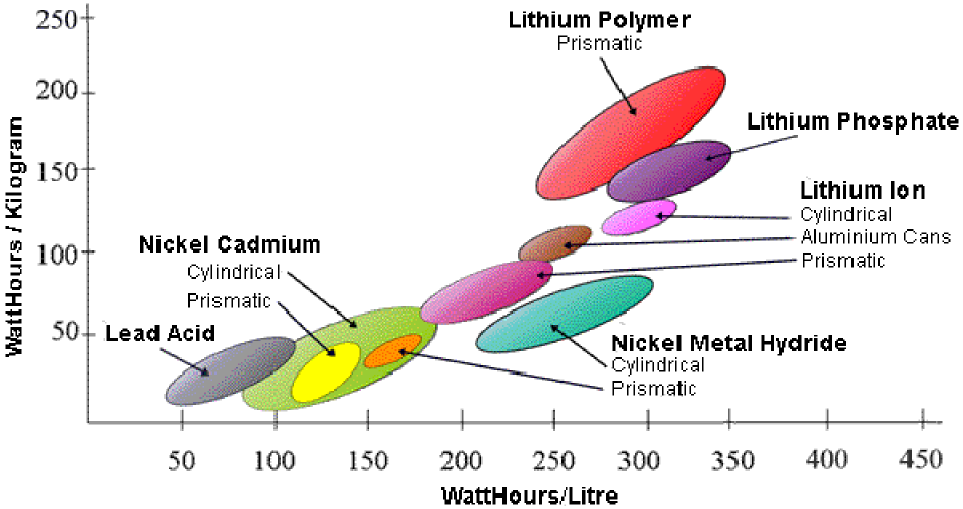


Technology Improvements

Design Case A

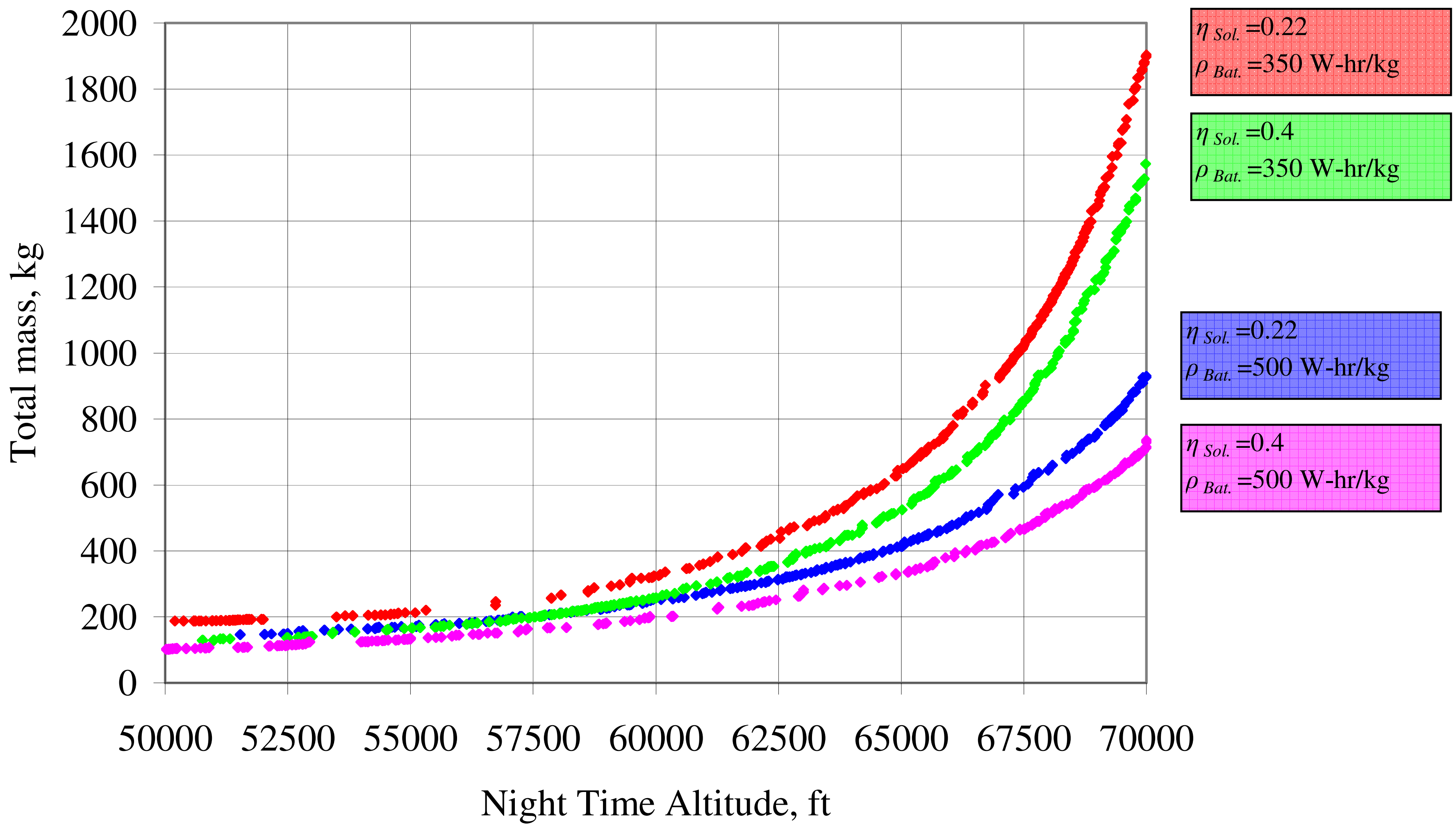
- Two main technologies:
  - Solar panels efficiency
    - Nominal 22%, Improved: 40%
  - Batteries energy density
    - Nominal 350 W-hr/kgf, Improved: 500 W-hr/kgf





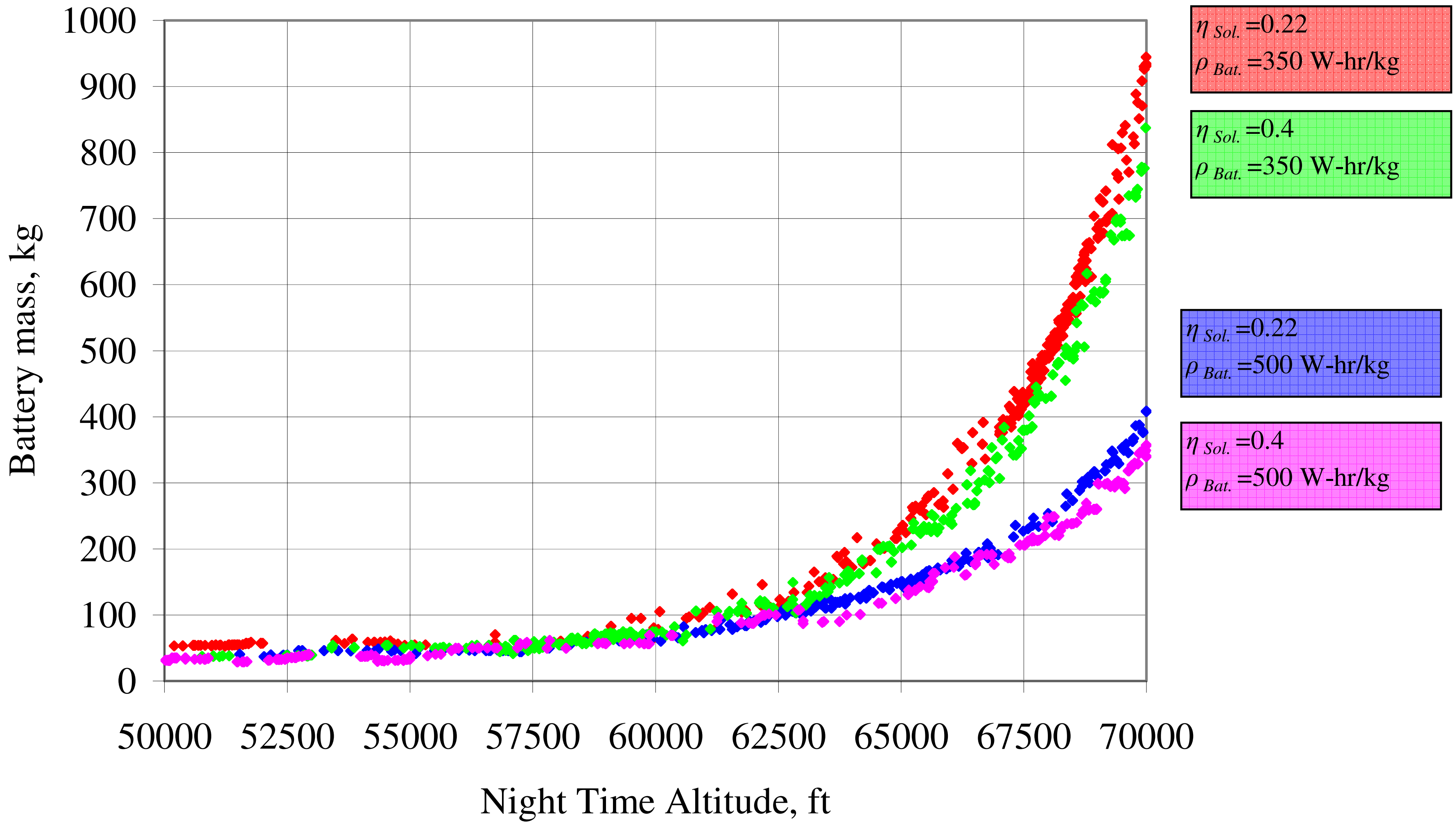
Technology Improvements

Total Mass



Technology Improvements

Battery Mass

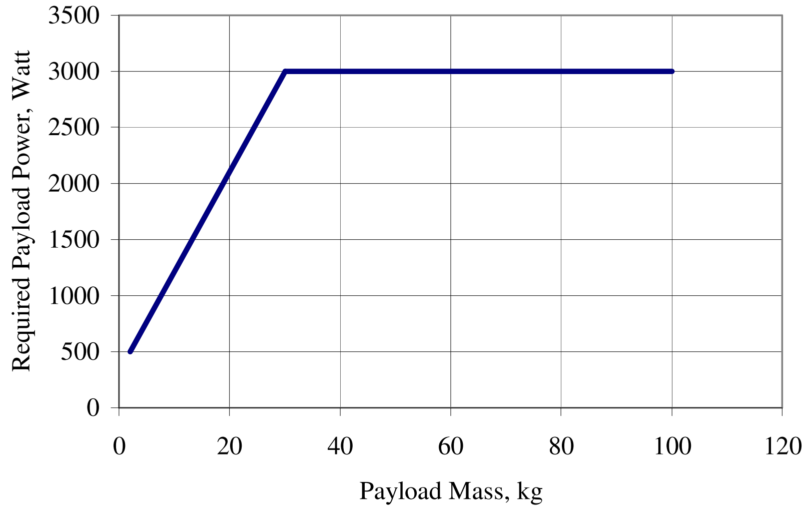


Design Case B

- Design Variables

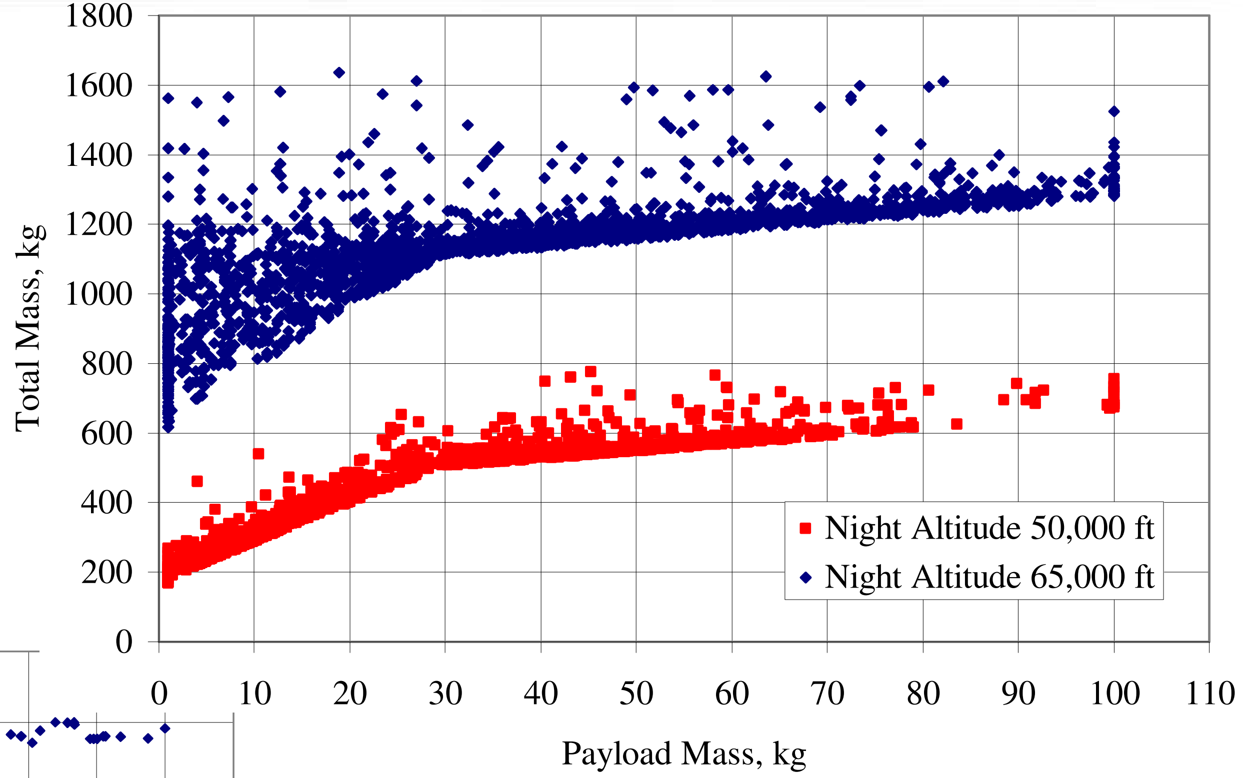
Design Variable	Minimum Value	Maximum Value
Battery mass, $m_{Battery}$	10 kg	500 kg
Aspect Ratio, AR	5	25
Wing Span, b	10 m	100 m

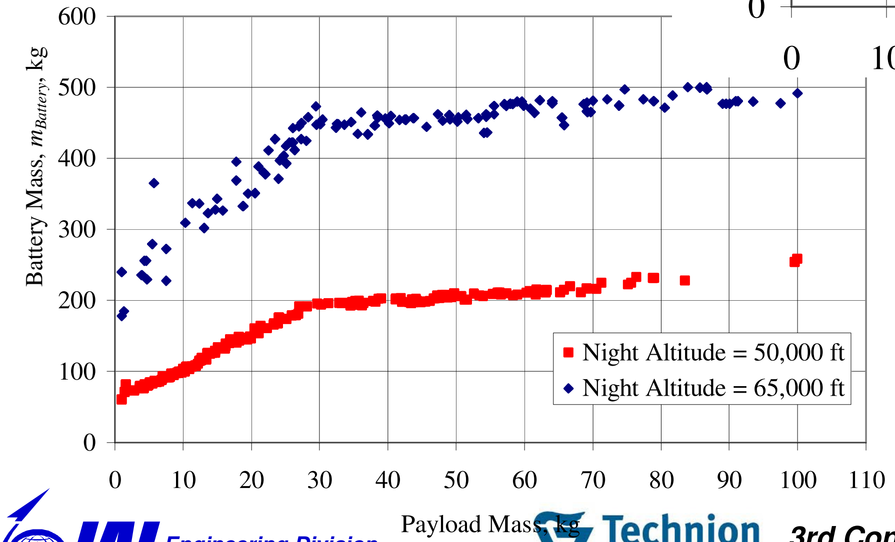
- Cost Function
  - Payload Mass - Maximize
  - Total Vehicle Mass – Minimize
  - Two cases
    - Night time altitude 65 kft
    - Night time altitude 50 kft



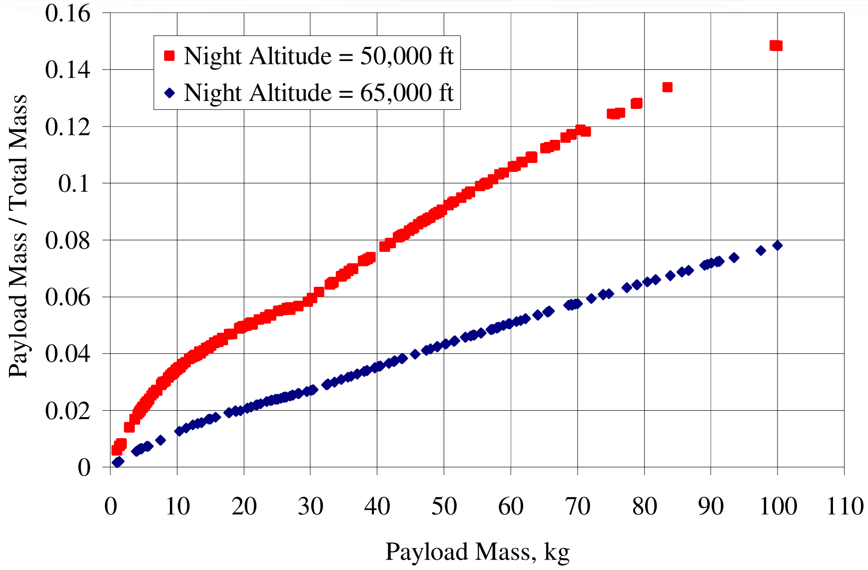
- Design Constraint
  - Energy balance

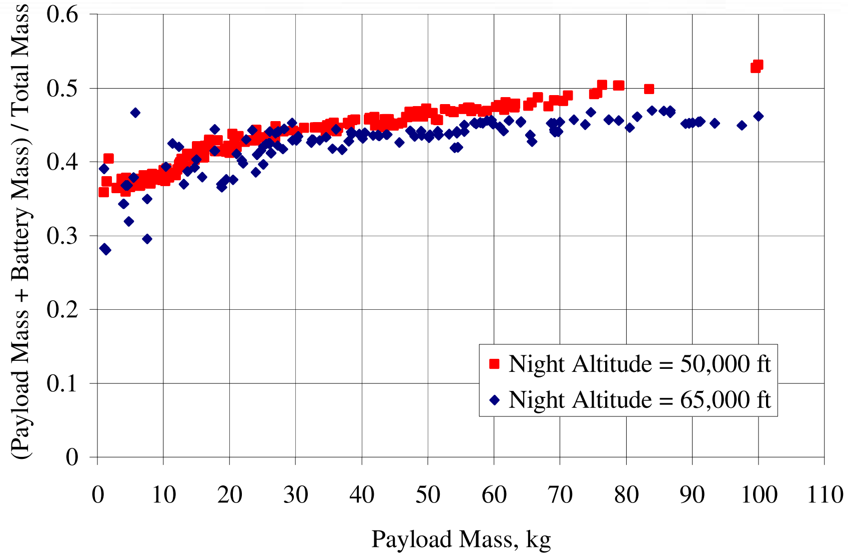
Design Case B, Pareto Front

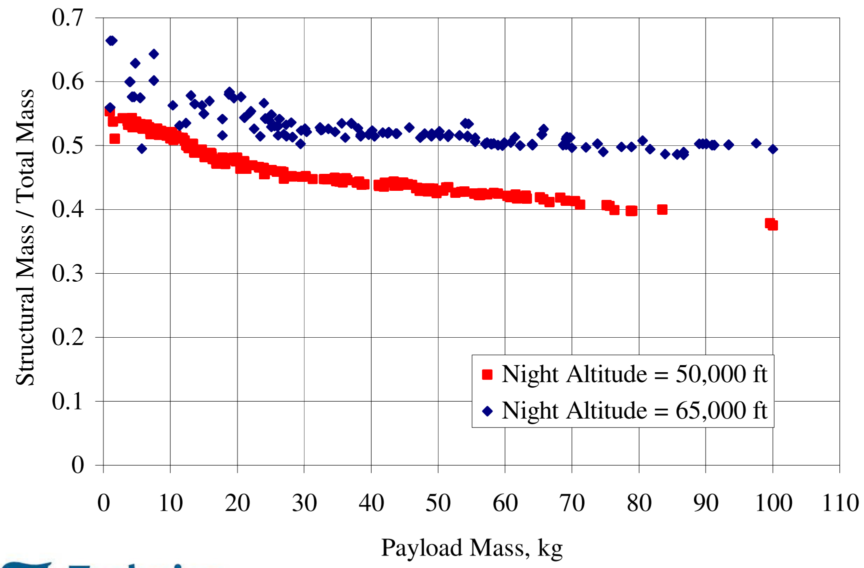




Design Case B, Pareto Front Designs







Conclusions

- Solar UAV design is a MDO problem
- Staying aloft ‘forever’ requires very big vehicles
  - Even for a very modest payload
- Low feasibility for constant altitude HALE
  - Lower night time altitude is required
- Crucial importance of improved technologies
  - Main effort: Energy storage weight and volume
  - Solar panels efficiency
  - Structure (Weight)