Robotic Mobility – Atmospheric Flight

- Gaseous planetary environments (Mars, Venus, Titan)
- Lighter-than-"air" (balloons, dirigibles)
- Heavier-than-"air" (aircraft, rotorcraft)

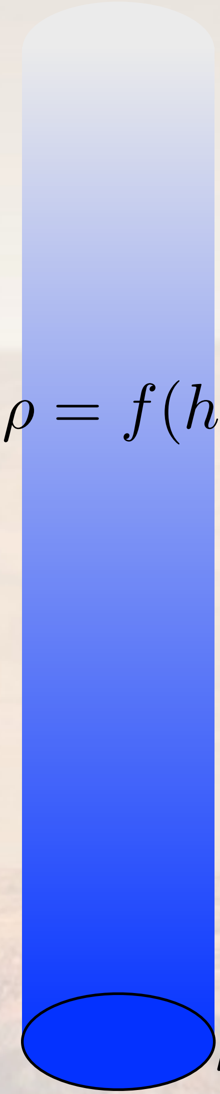
Exponential Atmospheres

$$\rho = \rho_o e^{-h/h_s}$$

$$\rho_o = \text{Reference density}$$

$$h_s = \text{Scale height}$$

Atmospheric Density with Altitude



$\rho = f(h)$

ρ_o, P_o

Pressure=the integral of the atmospheric density in the column above the reference area

$$P_o = \int_o^\infty \rho g dh = \rho_o g \int_o^\infty e^{-\frac{h}{h_s}} dh = -\rho_o g h_s \left[e^{-\frac{h}{h_s}} \right]_o^\infty$$

$$= -\rho_o g h_s \left[0 - 1 \right]$$

$$\boxed{P_o = \rho_o g h_s}$$

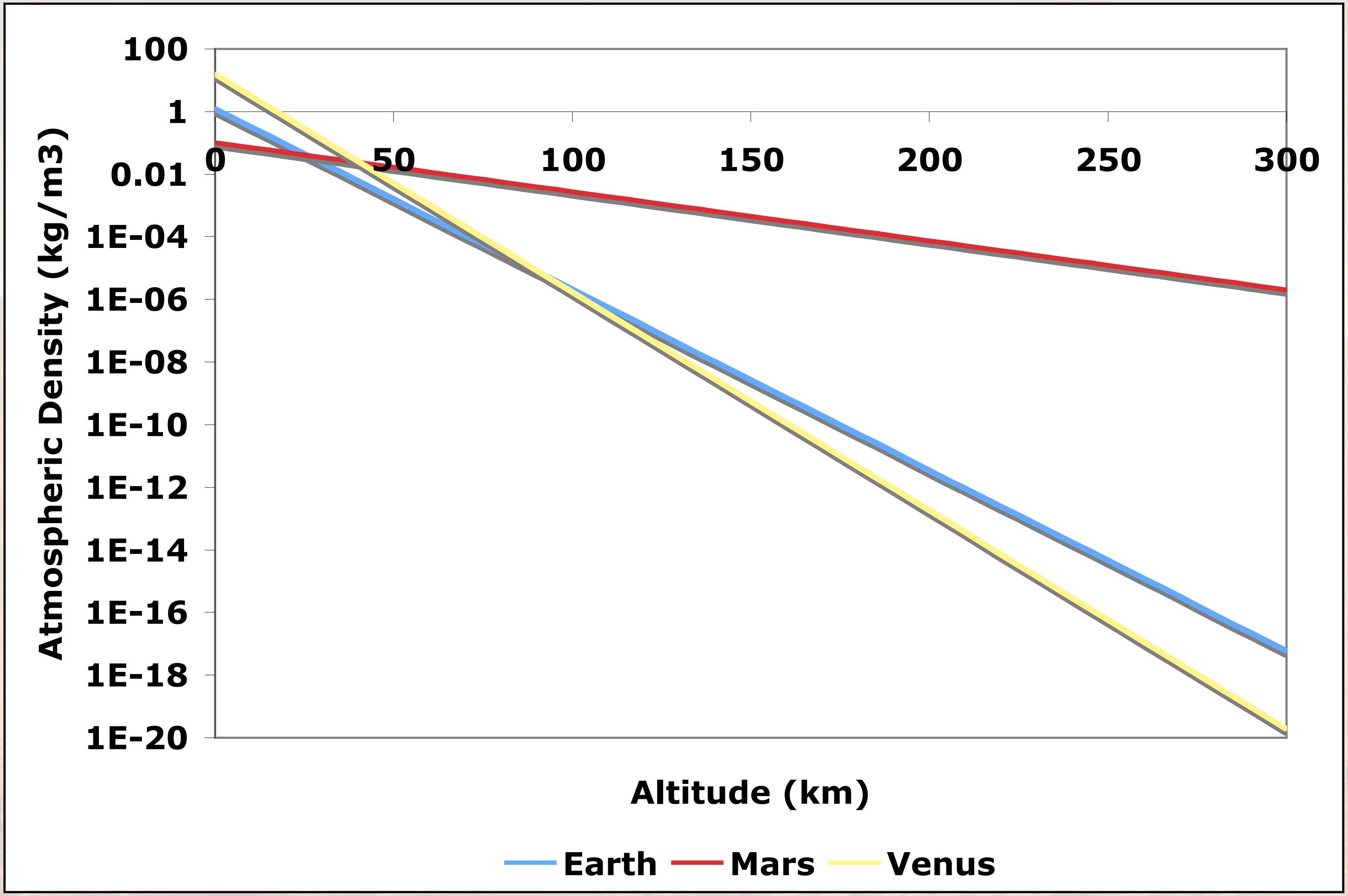
Earth: $\rho_o = 1.226 \frac{kg}{m^3}; \, h_s = 7524m;$

$$P_o(calc) = 90,400 \ Pa; \, P_o(act) = 101,300 \ Pa$$

Planetary Entry - Physical Data

	Radius (km)	μ (km	ρ_o (kg/m	h (km)	v (km/sec)
Earth	6378	398,604	1.225	7.524	11.18
Mars	3393	42,840	0.0993	27.7	5.025
Venus	6052	325,600	16.02	6.227	10.37
Titan			5.474	23.93	

Comparison of Planetary Atmospheres



Atmospheric Neutral Buoyancy

- Given an enclosed volume V of gas with density ρ
- Lift force is $V(\rho_{atm}-\rho)$ - must be $\geq mg$
  - on Earth ~1 kg lift/cubic meter of He
  - on Mars ~10 gms lift/cubic meter of He
- Horizontal velocity at equilibrium is identical to wind speed
- Interior pressure generally identical to ambient (except for superpressure balloons)
- Can generate low density through choice of gas, heating

Buoyancy by Light Gases

- Ideal gas law $PV = nRT$
- Given same volume and temperature, gas densities scale proportionally to molecular weight n
- Mars' atmosphere is essentially CO_2 – $n = 44$
  - He: $n = 4; \Delta \rho = 90.3\ gm/m^3$
  - H_2: $n = 2; \Delta \rho = 94.8\ gm/m^3$
- *Hindenburg* airship would have a total lift capacity of 49,894 kg in Mars atmosphere and gravity (Earth lift capacity 232,000 kg - factor of 4.6)

Thermal Balloons ("Montgolfieres")

- Use ambient gases and thermal difference to create lift
- Ideal gas – gas density inversely proportional to temperature
- Ambient atmospheric temperature on Mars ~200K
- Heat gases to 300K: lift force 33 gm/m^3 (about 1/3 of He or H_2 balloon)

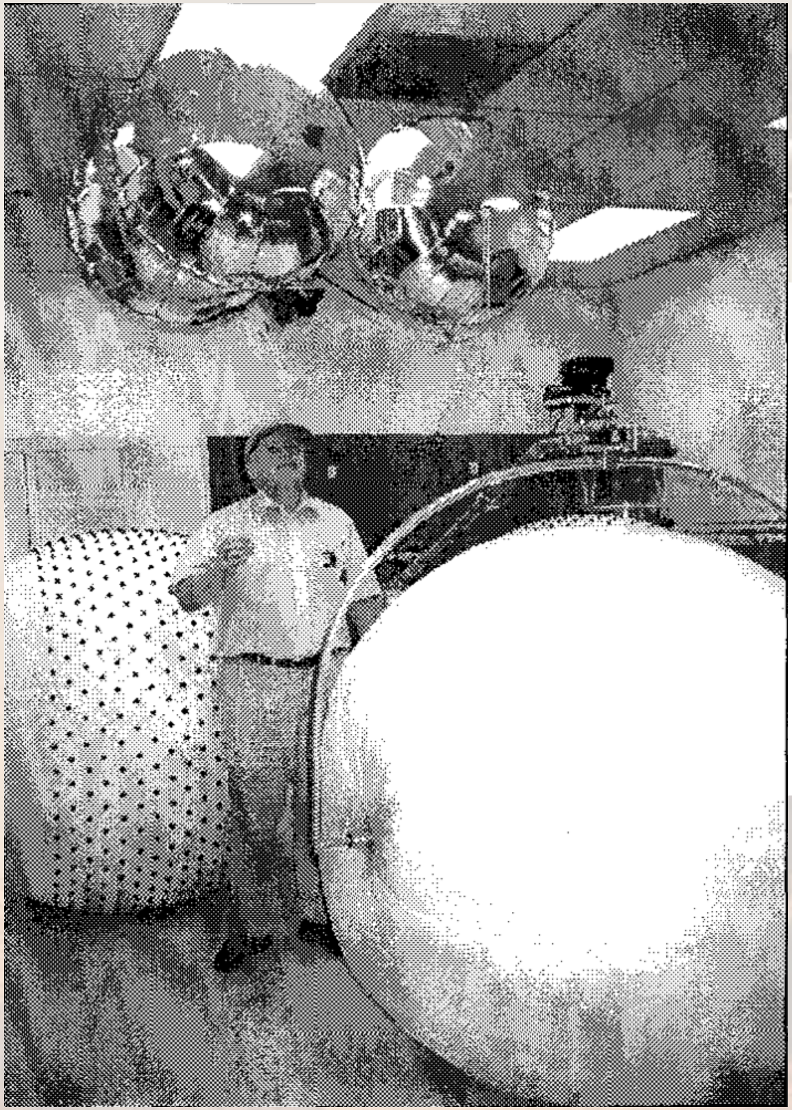
Superpressure Balloons

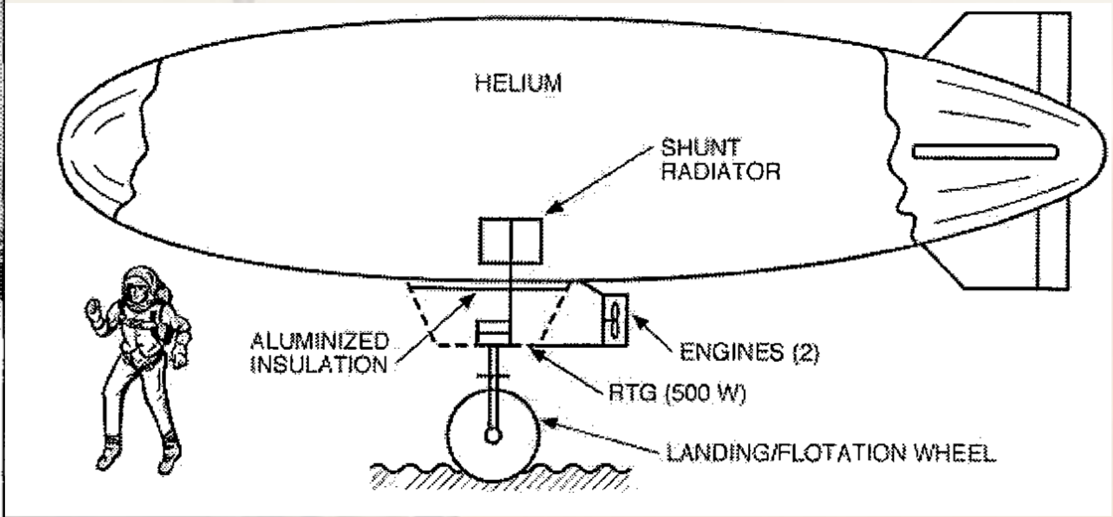
- Interior pressure greater than external ambient
- Envelope is relatively insensitive (in terms of volume) to interior pressure changes
- Diurnal temperature changes have minimal effect on lift
- Provides stable long-term platform for extended flights
- Envelope must be significantly stronger (and therefore heavier) than ambient-pressure balloons

Flight Missions with Balloons

- Venus: Vega - Russian Vega missions put two French balloons in Venus atmosphere in 1985
  - One died in 56 minutes
  - One operated for two days (battery limitations)
- Mars: French dual-balloon system (solar thermal balloon tied to He/H_2 balloon - gas balloon keeps solar balloon off the ground, thermal balloon lifts payloads when sun warms envelope) -never flew

Future Concepts – Titan Aerover

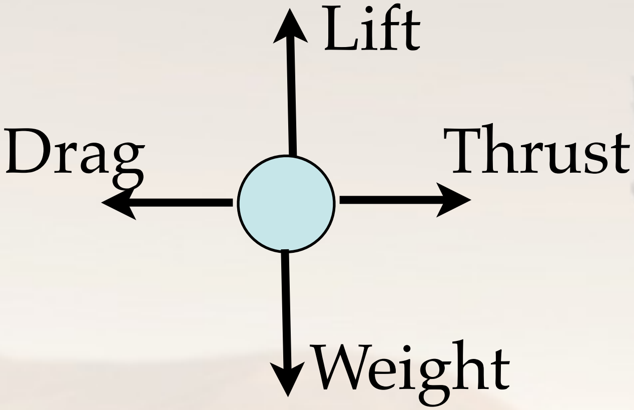




“Heavier than Atmosphere” Approaches

- Fixed wing
  - Gliders
  - Powered
    - Propellers
    - Jet
    - Rocket
- Rotary wing
- Hybrid/Reconfigurable

Dynamic Atmospheric Lift



$$D = \frac{1}{2}\rho v^2 S c_D$$

$$L = \frac{1}{2}\rho v^2 S c_L$$

For steady, level flight: $T = D \qquad L = W = mg$

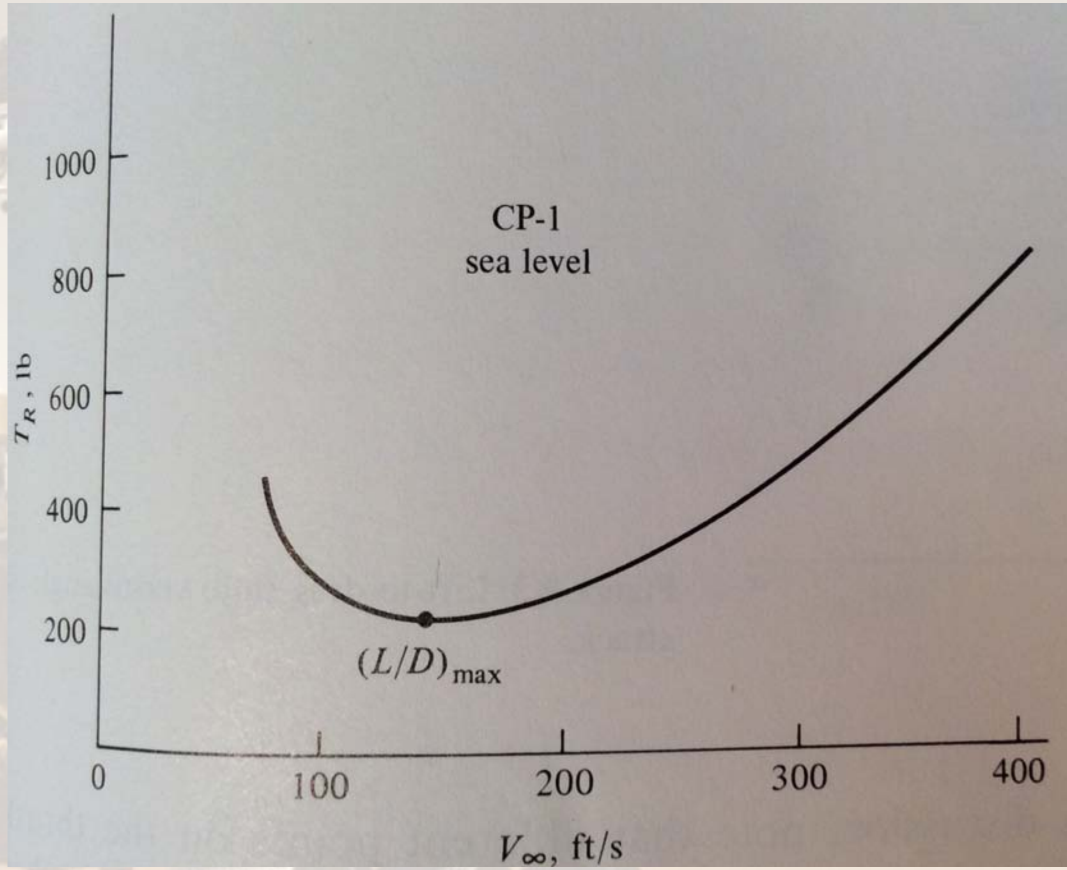
$$W = L = D\frac{L}{D} = T\frac{L}{D} \qquad T = \frac{W}{L/D}$$

$$L = \frac{1}{2}\rho v^2 S c_D \frac{L}{D}$$

Atmospheric Flight Performance

$$L = \frac{1}{2}\rho v^2 S c_L$$

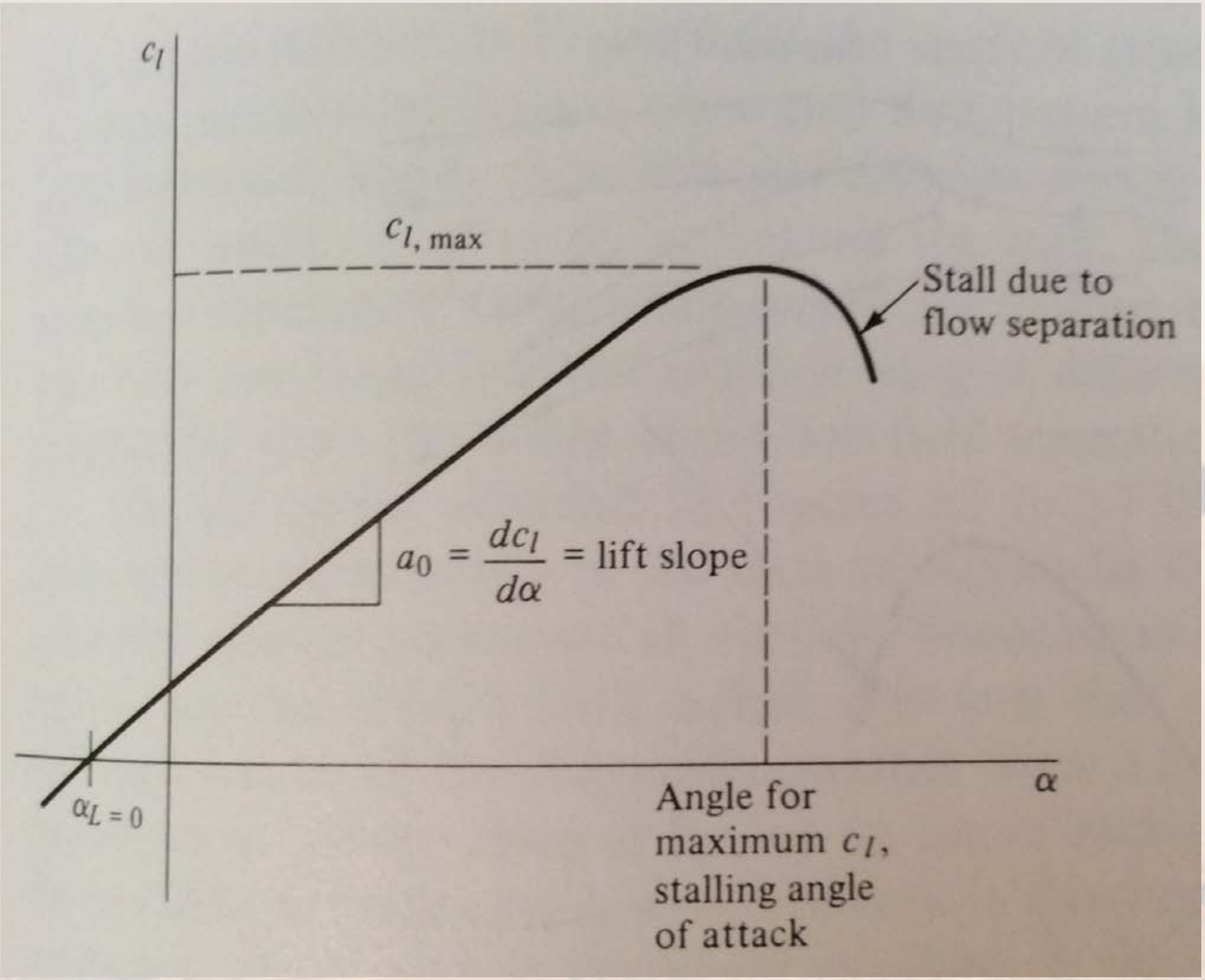
$$D = \frac{1}{2}\rho v^2 S c_D$$



from Anderson, *Introduction to Flight*, Third Edition McGraw Hill, 1989

$$c_D = c_{Do} + c_{Di} = c_{Do} + \frac{c_L^2}{\pi e(AR)}$$

Lift Curve



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Mars Atmosphere

$$\rho = 0.020 \ \frac{kg}{m^3}$$

$$T = 210 \ K$$

$$g = 3.71 \ \frac{m}{sec^2}$$

$$R = 188.92 \ \frac{J}{kg \ K}$$

$$\gamma = 1.2941$$

$$\text{Speed of sound } a = \sqrt{\gamma R T} = 226.6 \ \frac{m}{sec}$$

Aircraft Flight Performance

- U-2 high-altitude spy plane
- Cruises at "70,000+ feet"
- m=18,000 kg
- b=32 m
- S~64 m^2

$$v_{stall} = \sqrt{\frac{mg}{S}\frac{2}{\rho c_{L(max)}}}$$

$$\text{U-2 } v_{stall(Mars)} = 228.4\ \frac{m}{sec^2}$$

Stable Gliding Flight

Flight path angle γ

$$D = mg \sin \gamma$$

$$mg = W = L \implies \sin \gamma = \frac{1}{L/D}$$

High performance glider $L/D \approx 30$

Deploy at 10 km $\implies Range \approx 300\ km$

$$V \approx 200\ \frac{m}{sec} \implies \text{Flight time } 25\ min$$

Powered Flight

$$T = \dot{m}(v_e - V)$$

$$v_e = \text{Exhaust velocity; } V = \text{Flight velocity}$$

$$\text{Power into flow } P_f = \frac{\dot{m}}{2}\left(v_e^2 - V^2\right)$$

$$\text{Power into flight } P_v = TV$$

$$\text{Propulsive efficiency } \eta_{prop} = \frac{2}{1 + \frac{v_e}{V}}$$

Actuator Disk Size

Engine intake area A

$$\dot{m} = \rho A V \qquad T = D = \frac{W}{L/D}$$

$$T = \dot{m} V = \rho A V (v_e - V)$$

$$\rho A V (v_e - V) = \frac{W}{L/D}$$

$$A = \frac{W}{(L/D)\rho V (v_e - V)}$$

Rotorcraft (Quick and Dirty)

- Thrust is downwards
- Hovering flight T=W
- Power calculations same as before if L/D=1
- Incline lift vector angle β from vertical

$$W = T\cos\beta \Longrightarrow T = \frac{mg}{cos\beta}$$

$$D = T\sin\beta \Longrightarrow D = mg\tan\beta$$

$$\frac{1}{2}\rho V^2 S c_D = mg\tan\beta \Longrightarrow V = \sqrt{\frac{2mg\tan\beta}{\rho S c_D}}$$

Looking for Equation for Range

$$\text{Efficiency} = \frac{\text{propulsive power}}{\text{fuel power}} = \frac{Tv_e}{\dot{m}_f h}$$

$$\eta_{overall} = \frac{Tv_e}{\dot{m}_f h} \qquad \frac{dW}{dt} = -\dot{m}_f g = \frac{-W}{\frac{L}{D}\frac{T}{\dot{m}_f g}}$$

$$\frac{dW}{dt} = \frac{-Wv_e}{\frac{h}{g}\frac{L}{D}\frac{Tv_e}{\dot{m}_f h}} = \frac{-Wv_e}{\frac{h}{g}\frac{L}{D}\eta_{overall}}$$