Parametric Design

- The Design Process
- Regression Analysis
- Level I Design Example: Project Diana

Akin's Laws of Spacecraft Design - #3

Design is an iterative process. The necessary number of iterations is one more than the number you have currently done. This is true at any point in time.

Overview of the Design Process

Program Objectives ⇔ System Requirements

Vehicle-level Estimation (based on a few parameters from prior art)

System-level Estimation (system parameters based on prior experience)

System-level Design (based on discipline-oriented analysis)

Basic Axiom:

Relative rankings between competing systems will remain consistent from level to level

Increasing complexity

Increasing accuracy

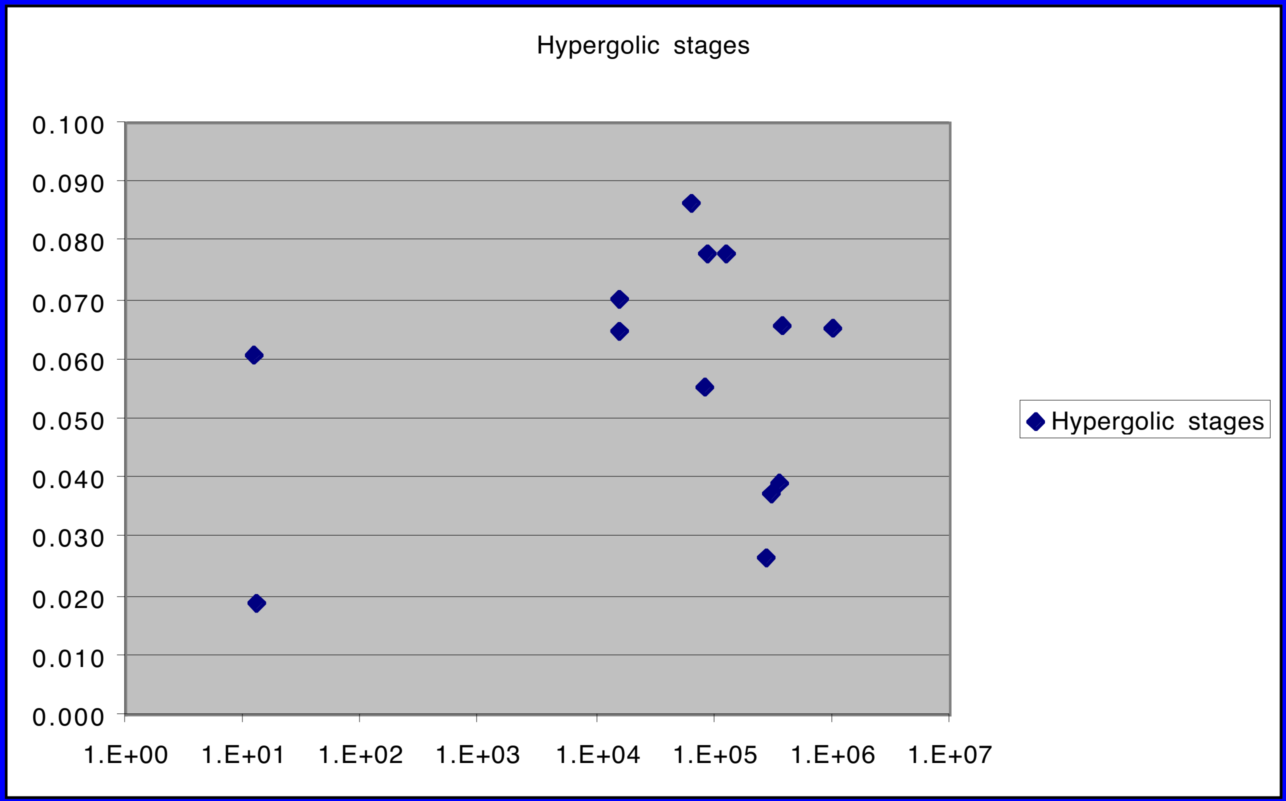
Decreasing ability to comprehend the "big picture"

Regression Analysis of Existing Vehicles

Veh/Stage	prop mass (lbs)	gross mass (lbs)	Type	Propellants	Isp vac (sec)	isp sl (sec)	sigma	eps	delta
Delta 6925 Stage 2	13,367	15,394	Storab	N2O4-A50	319.4		0.152	0.132	0.070
Delta 7925 Stage 2	13,367	15,394	Storab	N2O4-A50	319.4		0.152	0.132	0.065
Titan II Stage 2	59,000	65,000	Storab	N2O4-A50	316.0		0.102	0.092	0.087
Titan III Stage 2	77,200	83,600	Storab	N2O4-A50	316.0		0.083	0.077	0.055
Titan IV Stage 2	77,200	87,000	Storab	N2O4-A50	316.0		0.127	0.113	0.078
Proton Stage 3	110,000	123,000	Storab	N2O4-A50	315.0		0.118	0.106	0.078
Titan II Stage 1	260,000	269,000	Storab	N2O4-A50	296.0		0.035	0.033	0.027
Titan III Stage 1	294,000	310,000	Storab	N2O4-A50	302.0		0.054	0.052	0.038
Titan IV Stage 1	340,000	359,000	Storab	N2O4-A50	302.0		0.056	0.053	0.039
Proton Stage 2	330,000	365,000	Storab	N2O4-A50	316.0		0.106	0.096	0.066
Proton Stage 1	904,000	1,004,000	Storab	N2O4-A50	316.0	285.0	0.111	0.100	0.065
average					**312.2**	**285.0**	**0.100**	**0.089**	**0.061**
standard deviation					**8.1**		**0.039**	**0.033**	**0.019**

Regression Analysis of Inert Mass Fraction

Inert Mass Fraction



Stage Gross Mass (lbs)

Regression Analysis

- Given a set of N data points (x_i, y_i)
- Linear curve fit: y=Ax+B
  - find A and B to minimize sum squared error

$$error = \sum_{i=1}^{N} \left(Ax_i + B - y_i \right)^2$$

  - Analytical solutions exist, or use Solver in Excel
- Power law fit: $y=Ax^B$

$$error = \sum_{i=1}^{N} \left[A\log(x_i) + B - \log(y_i) \right]^2$$

- Polynomial, exponential, many other fits possible

Regression Values for Design Parameters

	Isp (vac) (sec)	delta	Max ΔV (m/sec)
LOX/LH2	433	0.078	10825
LOX/RP-1	320	0.063	8670
Storables	312	0.061	8552
Solids	283	0.087	6772

Additional Issues for Parametric Analysis

- Propulsion system design
- Structural mass estimates
- Propellant performance
- Costing factors
- Scaling factors
- Etc…

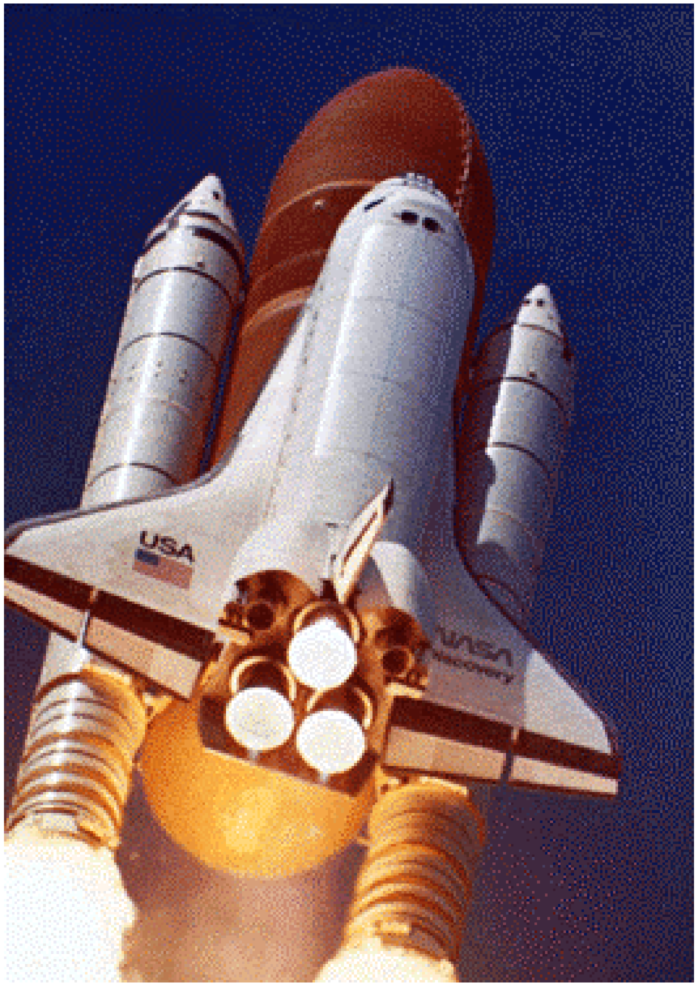
Project Diana Objective

Design a system to return humans to the moon before the end of this decade for the minimum achievable cost.

Applicable Requirements

- System must be based on the use of American launch vehicles in operational status as of 2005
- System shall be at least as capable for lunar exploration as the J-mission Apollo system
  - Two landed crew
  - 72 hour stay time, 3 x 6 hour EVAs
  - 300 kg of science payload (each way)

U.S. Heavy-Lift Vehicles (2005)



- Space Shuttle - 27K kg to LEO
- Delta IV Heavy - 23K kg to LEO

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Lunar Mission ΔV Requirements

To: / From:	Low Earth Orbit	Lunar Transfer Orbit	Low Lunar Orbit	Lunar Descent Orbit	Lunar Landing
Low Earth Orbit		3.107 km/sec			
Lunar Transfer Orbit	3.107 km/sec		0.837 km/sec		3.140 km/sec
Low Lunar Orbit		0.837 km/sec		0.022 km/sec	
Lunar Descent Orbit			0.022 km/sec		2.684 km/sec
Lunar Landing		2.890 km/sec		2.312 km/sec	

Mission Scenario 1

- **What can be accomplished with a single shuttle payload (27K kg)?**
- **Assume δ=0.1, Isp=320 sec**
- **Direct landing**
  - **LEO-lunar transfer orbit ΔV=3.107 km/sec**
  - **Lunar transfer orbit-lunar landing ΔV=3.140 km/sec**
  - **Lunar surface-earth return orbit ΔV=2.890 km/sec**
  - **Direct atmospheric entry to landing**

Scenario 1 Analysis

- **Trans-lunar injection**

$$r_{TLI} = e^{-\frac{\Delta V_{TLI}}{g I_{sp}}} = 0.3713$$

$$m_{TLI} = m_o\left(r_{TLI} - \delta\right) = 27{,}000(0.3713 - 0.1) = 7325\ kg$$

- **Lunar landing**
  - **r=0.3674**
  - **m_{LS}=1958 kg**
- **Earth return**
  - **r=0.3978**
  - **m_{ER}=583 kg**

This scenario would work for a moderate robotic sample return mission, but is inadequate for a human program.

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Mission Scenario 2

- Assume a single shuttle payload is used to size the lunar descent and ascent elements
  - Shuttle payload performs landing and return
  - "Something else" performs TLI for shuttle payload
- Assume δ=0.1, Isp=320 sec
- Direct landing (unchanged from Scenario 1)
  - LEO-lunar transfer orbit ΔV=3.107 km/sec
  - Lunar transfer orbit-lunar landing ΔV=3.140 km/sec
  - Lunar surface-earth return orbit ΔV=2.890 km/sec
  - Direct atmospheric entry to landing

Scenario 2 Analysis

- **Lunar landing (27,000 kg at lunar arrival)**
  - **$r=0.3674$**
  - **$m_{LS}=7219$ kg**
- **Earth return**
  - **$r=0.3978$**
  - **$m_{ER}=2150$ kg**
- **Trans-lunar injection**
  - **$r=0.3713$**

$$m_{LEO} = \frac{m_{TLI}}{(r_{TLI} - \delta)} = 99{,}520\ kg$$

Payload mass still too low for human spacecraft. TLI stage mass of 72,520 kg is too large for any existing launch vehicle.

Mission Scenario 3

- Assume three Delta-IV Heavy missions carry identical boost stages which perform TLI and part of descent burn
- Space shuttle payload completes descent and performs ascent and earth return
- All other factors as in previous scenarios

Scenario 3 Standard Boost Stage

- m_o=23,000 kg
- m_i =2300 kg
- m_p =20,700 kg
- LEO departure configuration is three boost stages with 27,000 kg descent/ascent stage as payload
- m_{LEO} =96,000 kg

Scenario 3 TLI Performance

- **Boost stage 1**

$$\Delta V_1 = -gI_{sp} \ln\left(\frac{m_{LEO} - m_{prop}}{m_{LEO}}\right) = 762 \, {}^{m}\!/_{\sec}$$

  - **V_{TLI} remaining=2345 m/sec**
- **Boost stage 2**
  - **r=0.7; ΔV_2=1046 m/sec**
  - **V_{TLI} remaining=1300 m/sec**
- **Boost stage 3**
  - **r=0.55; ΔV_3=1300 m/sec**
  - **Residual ΔV after TLI=376 m/sec**
- **Total booster performance=3484 m/sec**

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Alternate Staging Possibilities

- Three identical stages
- Serial staging (previous chart) ΔV=3483 m/sec
- Parallel staging (all three) ΔV=3264 m/sec
- Parallel/serial staging (2/1) ΔV=3446 m/sec

➥ Pure serial staging is preferred

Ascent/Descent Performance

- 376 m/sec of lunar descent maneuver performed by boost stage 4
- Remaining descent requires 2764 m/sec
  - $r=0.4143$
  - $m_i=2700$ kg
  - $m_{LS}=8485$ kg
- Earth return
  - $r=0.3978$
  - $m_i=849$ kg
  - $m_{ER}=2528$ kg

Return vehicle mass is still significantly below that of the Gemini spacecraft - need to examine other numbers of boost vehicles

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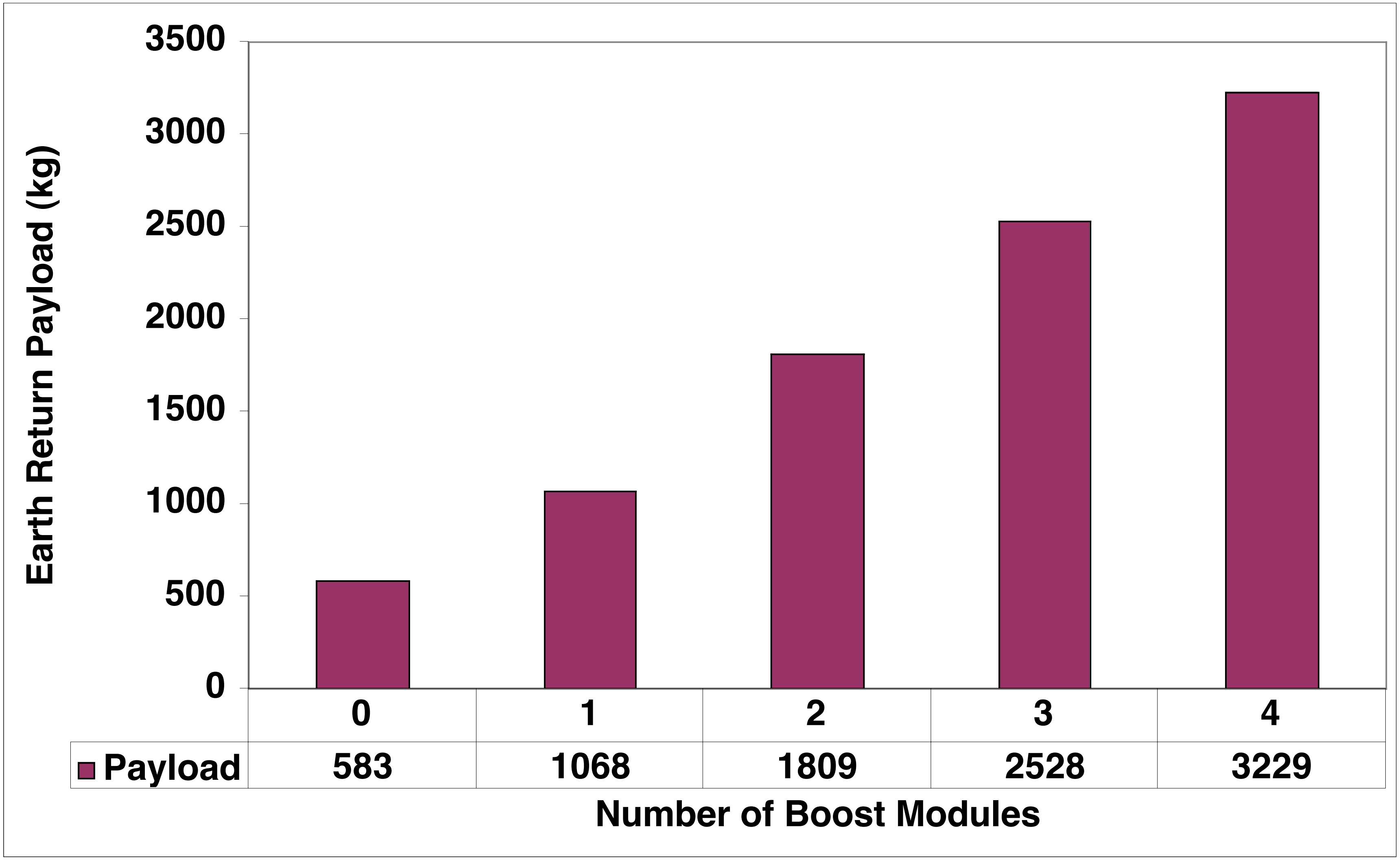
Effect of Number of Boost Stages

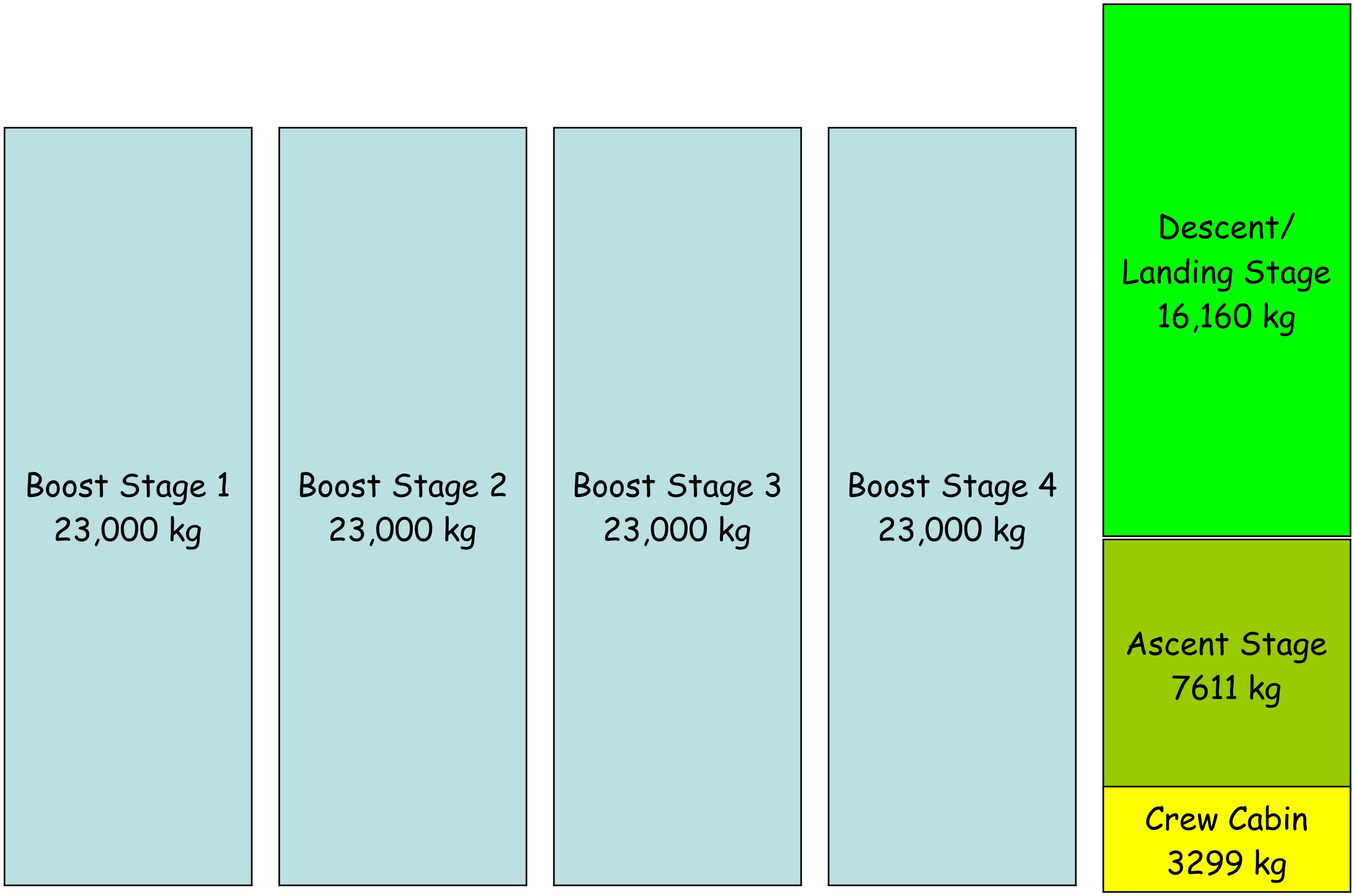


	0	1	2	3	4
Payload	583	1068	1809	2528	3229

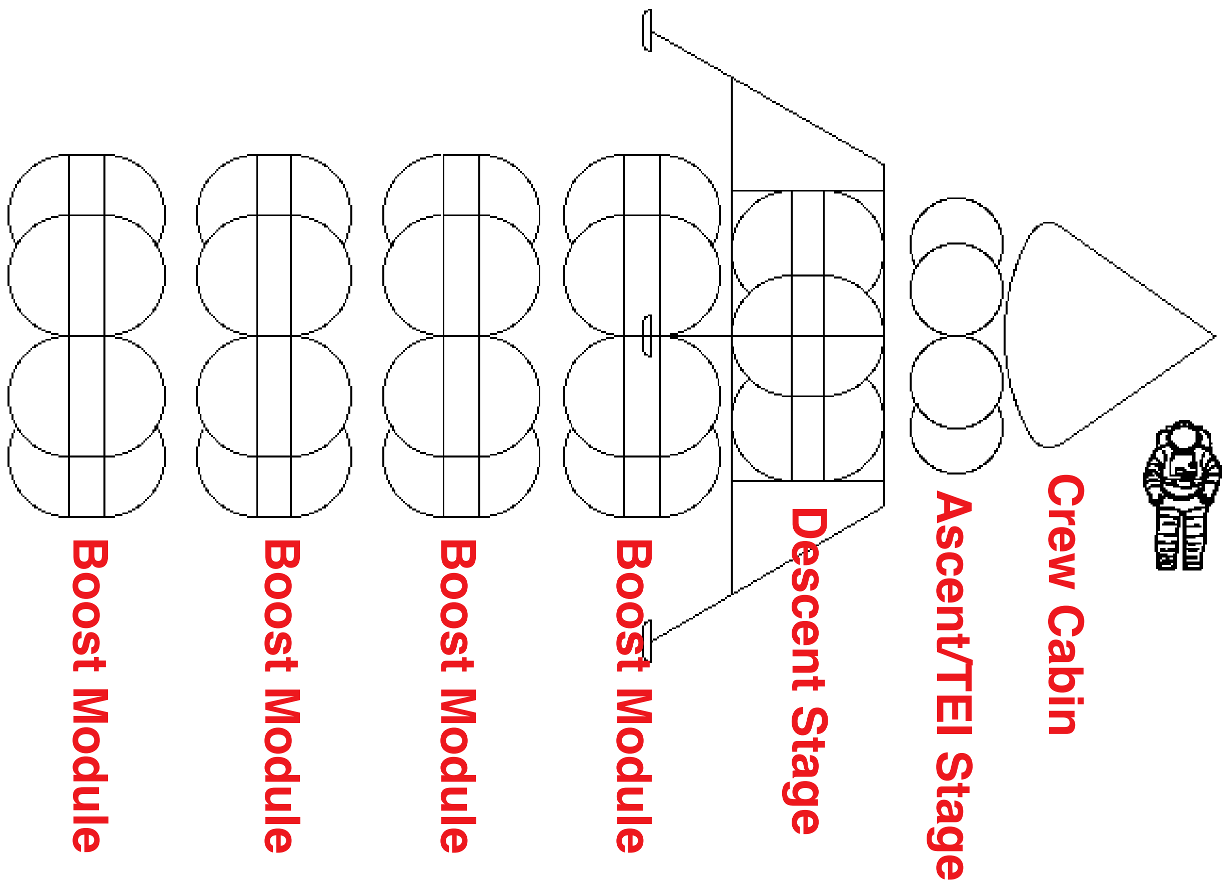
Creating a Baseline

- Need to modify Scenario 3 to provide more than 3000 kg of Earth return mass (Gemini-class spacecraft)
- Select 4 boost modules based on trade study performed
- Repeat calculations
- Establish as an early baseline: something to use as standard, vary parameters to identify promising modifications
- Often termed “strawman” design
- It won’t last!!! Design iteration will continue

Baseline System Schematic



Initial Configuration Sketch



Akin's Laws of Spacecraft Design - #20

(von Tiesenhausen's Law of Engineering Design) If you want to have a maximum effect on the design of a new engineering system, learn to draw. Engineers always wind up designing the vehicle to look like the initial artist's concept.

Transport Architecture Options

- Transportation node at intermediate point (low lunar orbit, Earth-Moon L1)
- Leave systems at node if not needed on the lunar surface, e.g.:
  - TransEarth injection stage
  - Orbital life support module
  - Entry, descent, and landing systems
- Will increase payload capacities at the expense of additional operational complexity, potential for additional safety critical failures

Variation 1: Lunar Orbit Staging

- Assume same process as baseline, but use lunar parking orbit before/after landing
- Additional ΔV's required for LLO stops
  - Lunar landing additional ΔV=+31 m/sec
  - Lunar take-off additional ΔV=+53 m/sec
- Low lunar orbit waypoint changes baseline payload to 3118 kg (-3.5%)
- Not useful without taking advantage of node to limit lunar landing mass

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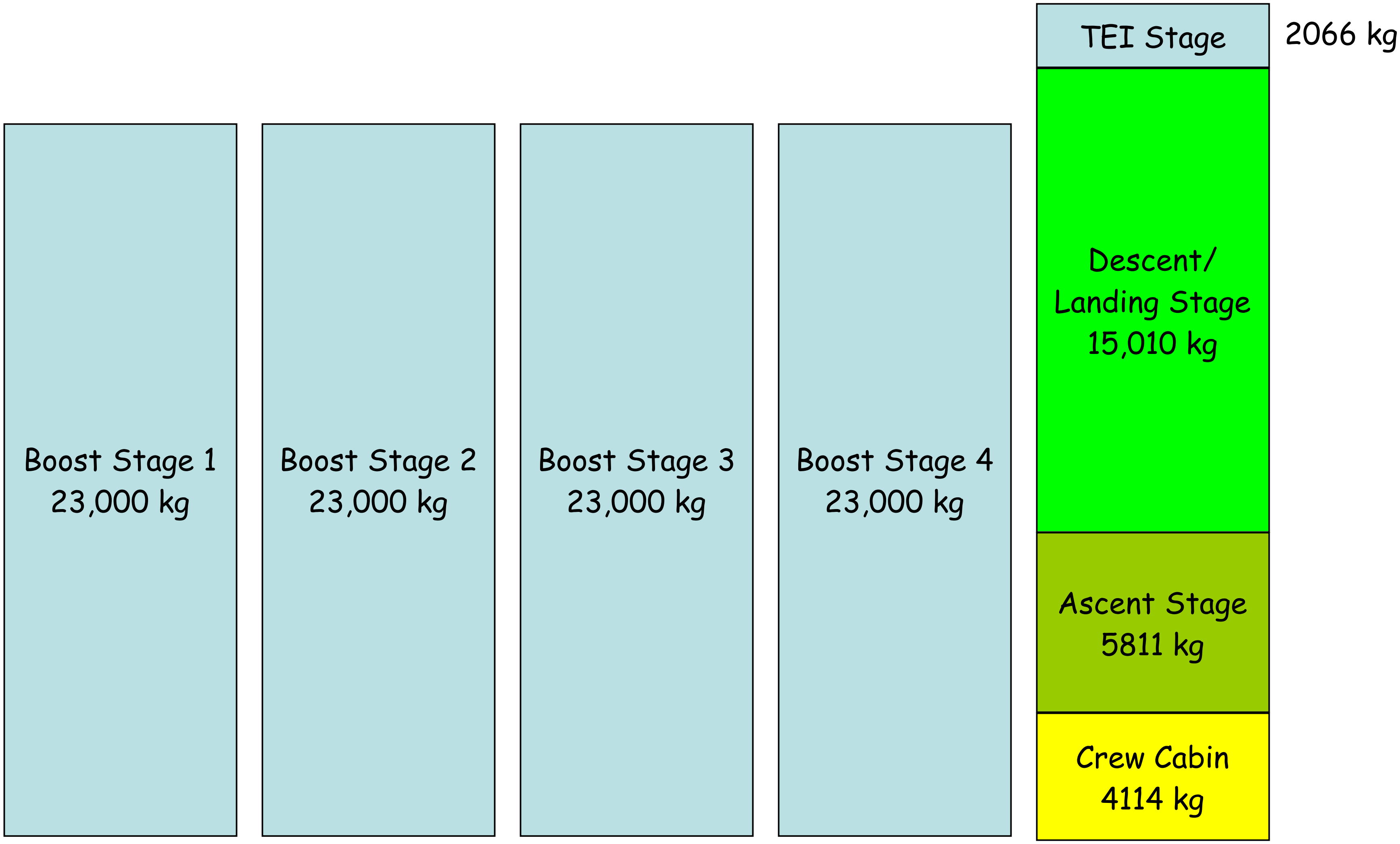
Variation 2: Lunar Orbit Rendezvous

- Use specialized vehicle for descent/ascent
- Use four boost stages as per baseline
- Boost stage 4 residual propellants
  - 10,680 kg following trans lunar insertion
  - 1315 kg following lunar orbit insertion
  - Use remaining stage 4 capacity to aid descent stage
- Leave TEI stage in lunar orbit during ascent/descent
  - Descent ΔV=2334 m/sec
  - Ascent ΔV=2084 m/sec
  - TEI ΔV=837 m/sec

LOR System Schematic



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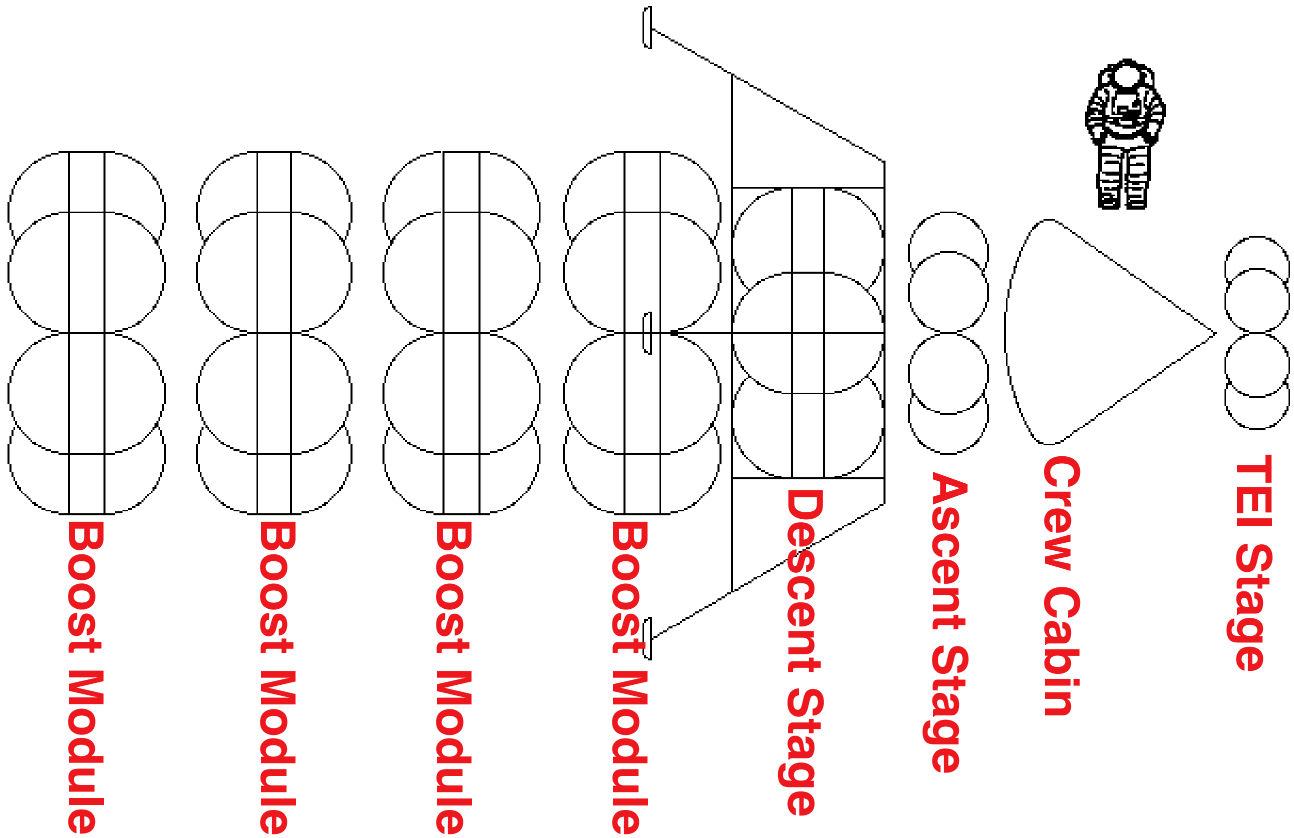
Variation 2 Sketch



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Variation 3: Maximal LOR

- Retain all features of Variation 2:
  - Use specialized vehicle for descent/ascent
  - Use four boost stages as per baseline
  - Boost stage 4 residual propellants
    - 10,680 kg following trans lunar insertion
    - 1315 kg following lunar orbit insertion
    - Use remaining stage 4 capacity to aid descent stage
  - Leave TEI stage in lunar orbit during ascent/descent
- Also leave equipment for earth return and entry in lunar orbit
  - Heat shield
  - Parachutes
  - Total assumed mass = 1000 kg

Akin's Laws of Spacecraft Design - #9

Not having all the information you need is never a satisfactory excuse for not starting the analysis.

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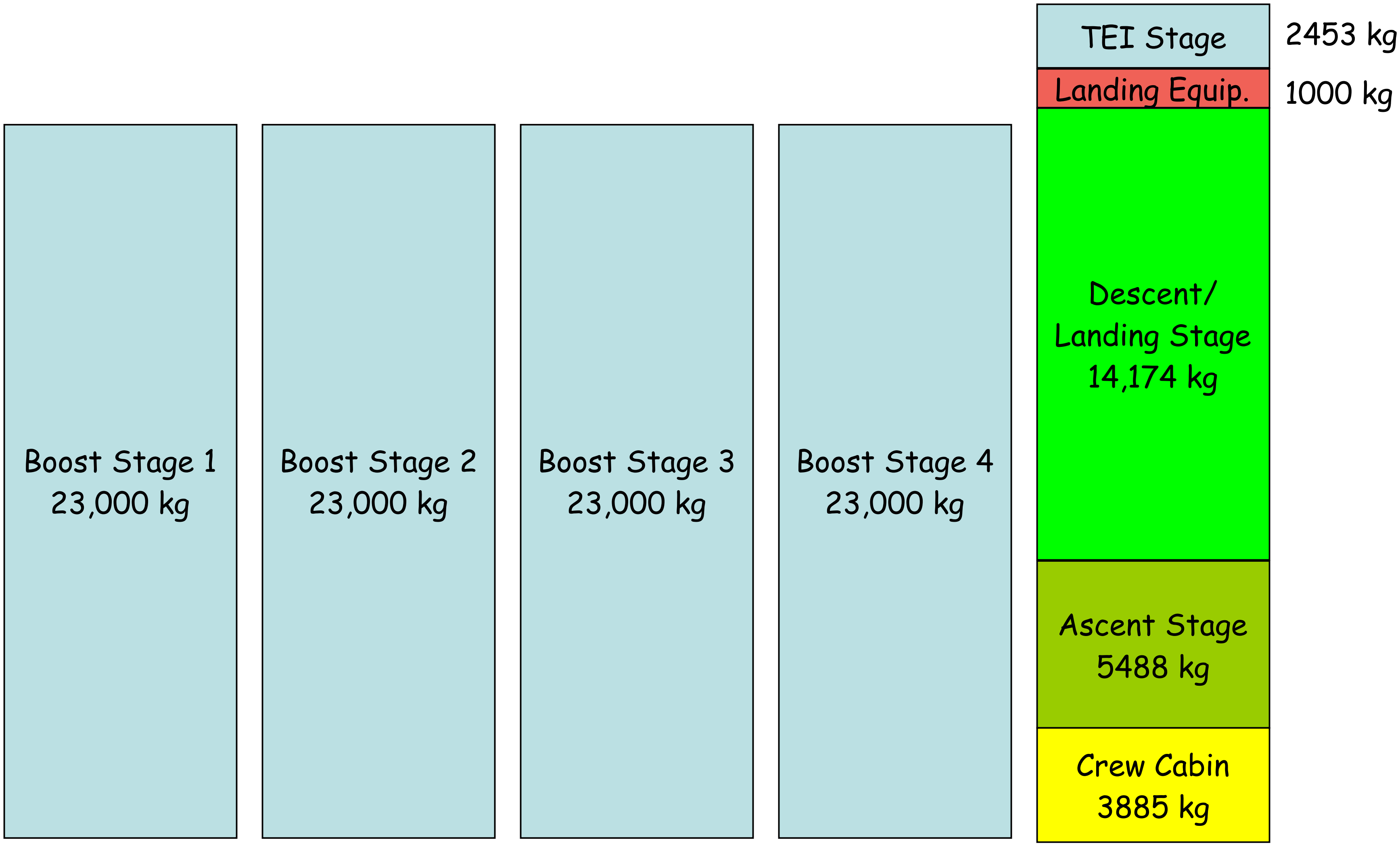
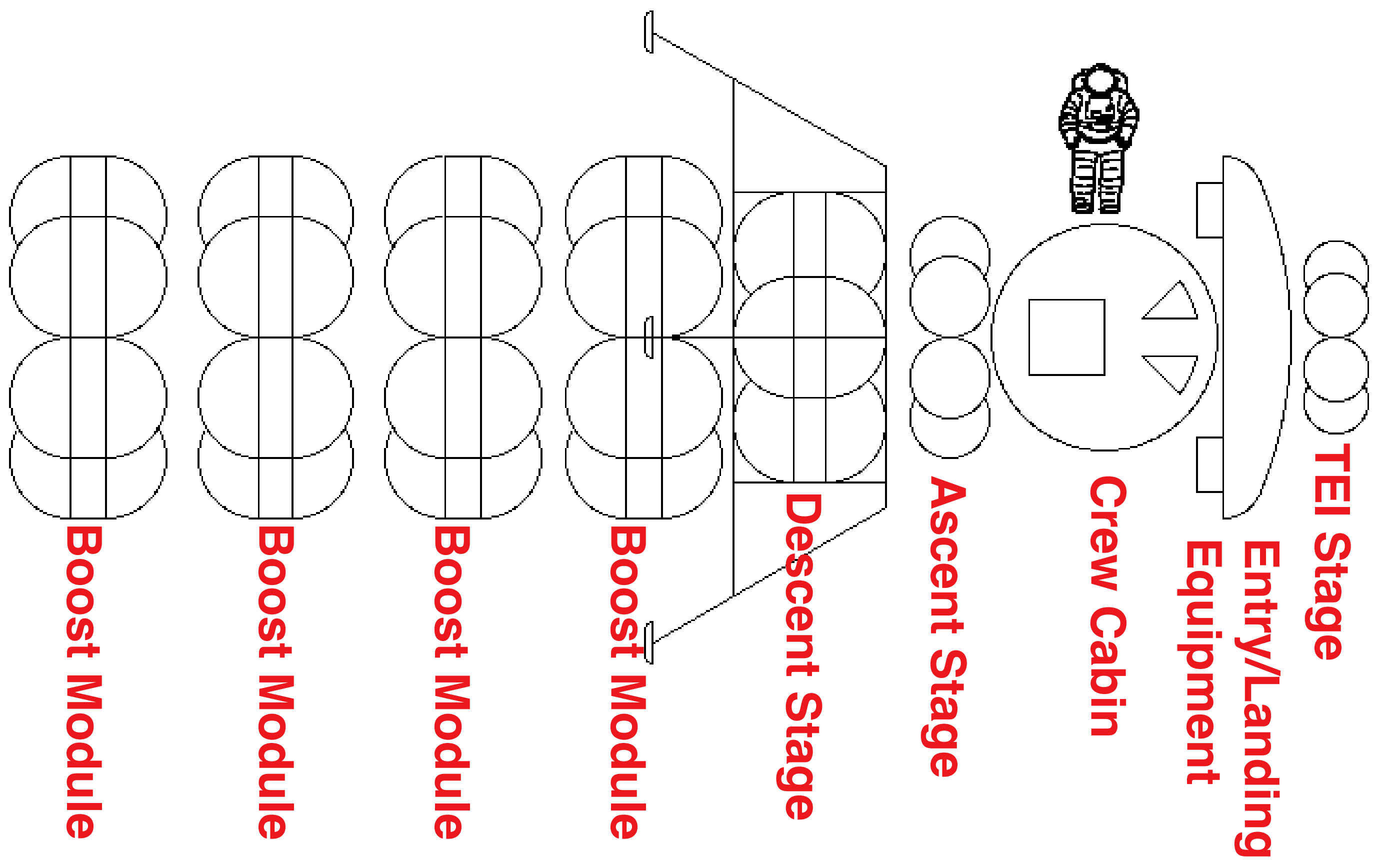
Variation 3 System Schematic



Variation 3 Sketch



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Akin's Laws of Spacecraft Design - #10

When in doubt, estimate. In an emergency, guess. But be sure to go back and clean up the mess when the real numbers come along.

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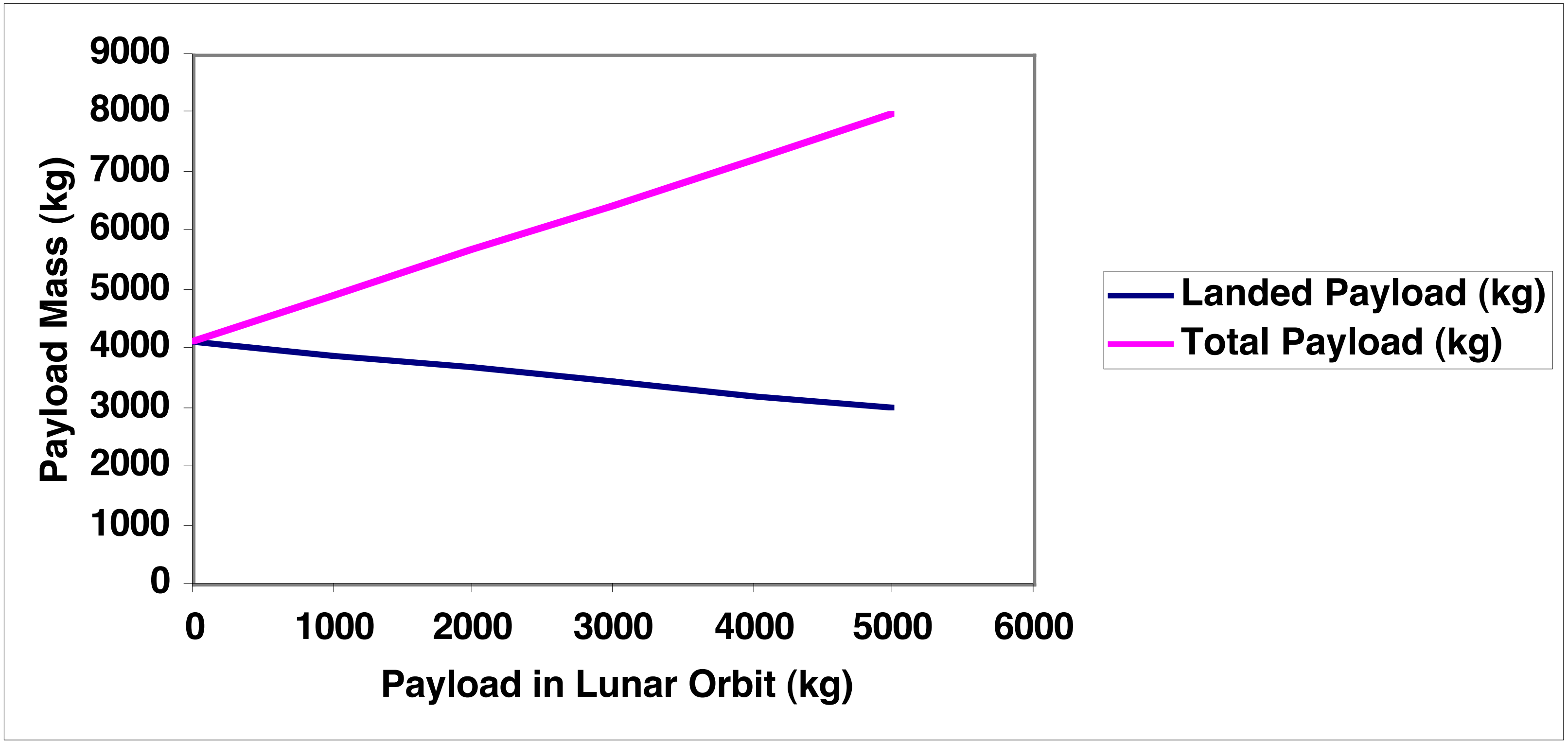
Sensitivity to Orbital Payload



- **One kg on surface = 4.4 kg in orbit**
- **Mass left in orbit increases total payload by 30%**

The Next Steps From Here

- **Perform parametric sensitivity analyses**
  - **Inert mass fractions**
  - **Specific impulse**
- **Investigate reduction from 4 to 3 boost stages for minimal system**
- **Trade studies, e.g.**
  - **2 crew cabins vs. 1**
  - **Cryo first stage for TLI**
- **Reach decision(s) on revision of baseline design**
- **Configuration design**

Overview of the Design Process