HELIOPOLIS

The Next Giant Leap

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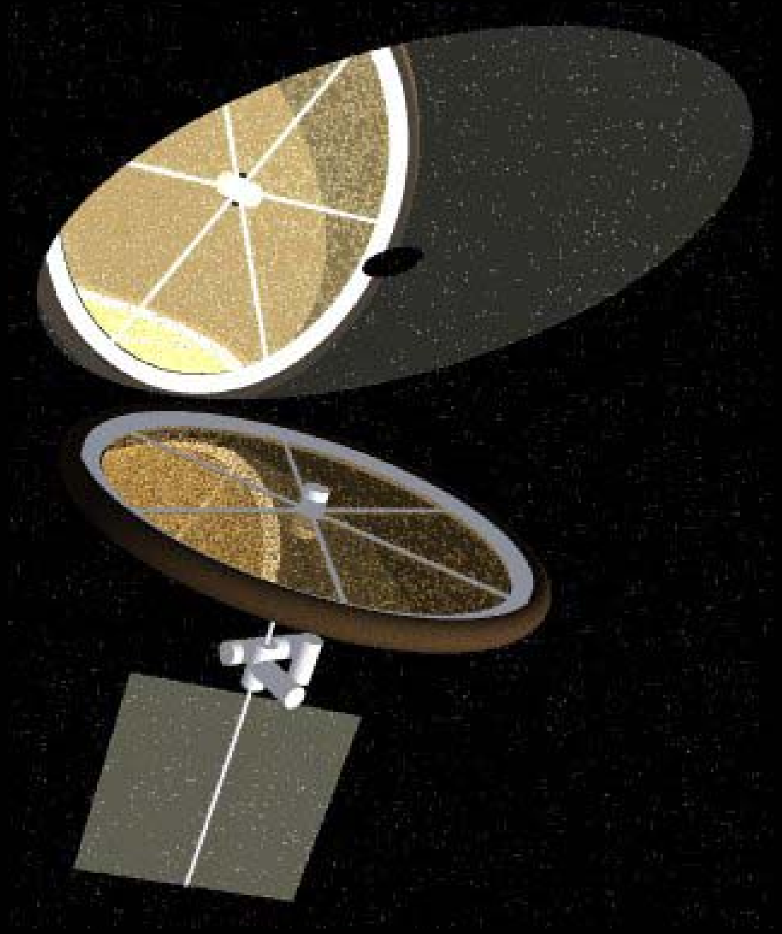
Heliopolis Mission

To build a profitable,
self-sustaining foothold
for
humanity in space

Heliopolis:

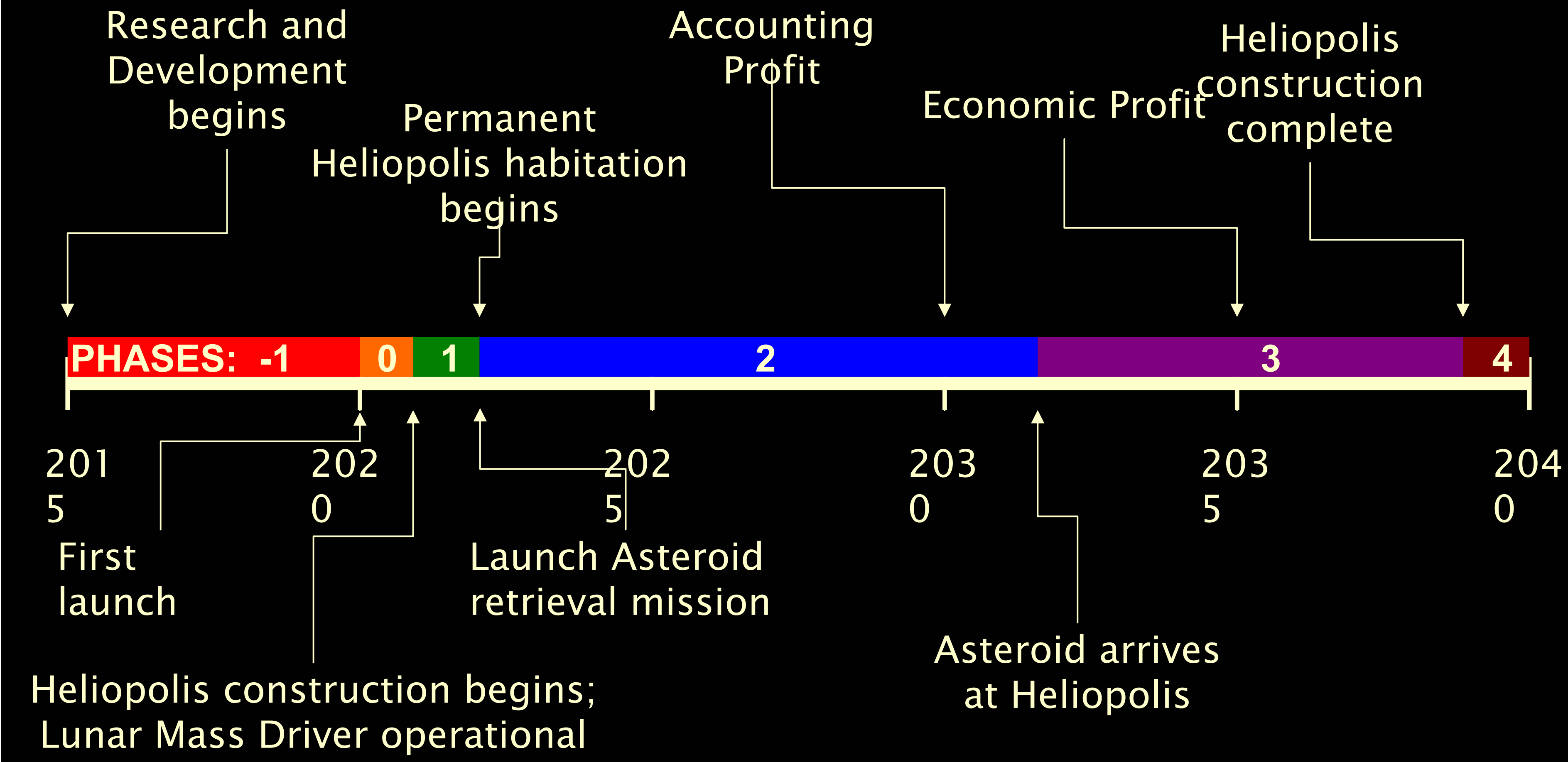
Space Business Park / Community

- Support several industries
  - Solar power satellites (SPS)*
  - Communications satellites
  - Zero-gravity manufacturing
  - Tourism
  - Asteroid mining
  - Capacity for growth (self-replication)
- Lunar L1 halo orbit
  - Continuous sunlight
  - Moon-viewing for tourists
- Necessary for future space infrastructure



*Only revenue from SPS modeled

Heliopolis Development Timeline



Research and Development begins

Permanent Heliopolis habitation begins

Accounting Profit

Economic Profit

Heliopolis construction complete

PHASES: -1

0

1

2

3

4

2015

2020

2025

2030

2035

2040

First launch

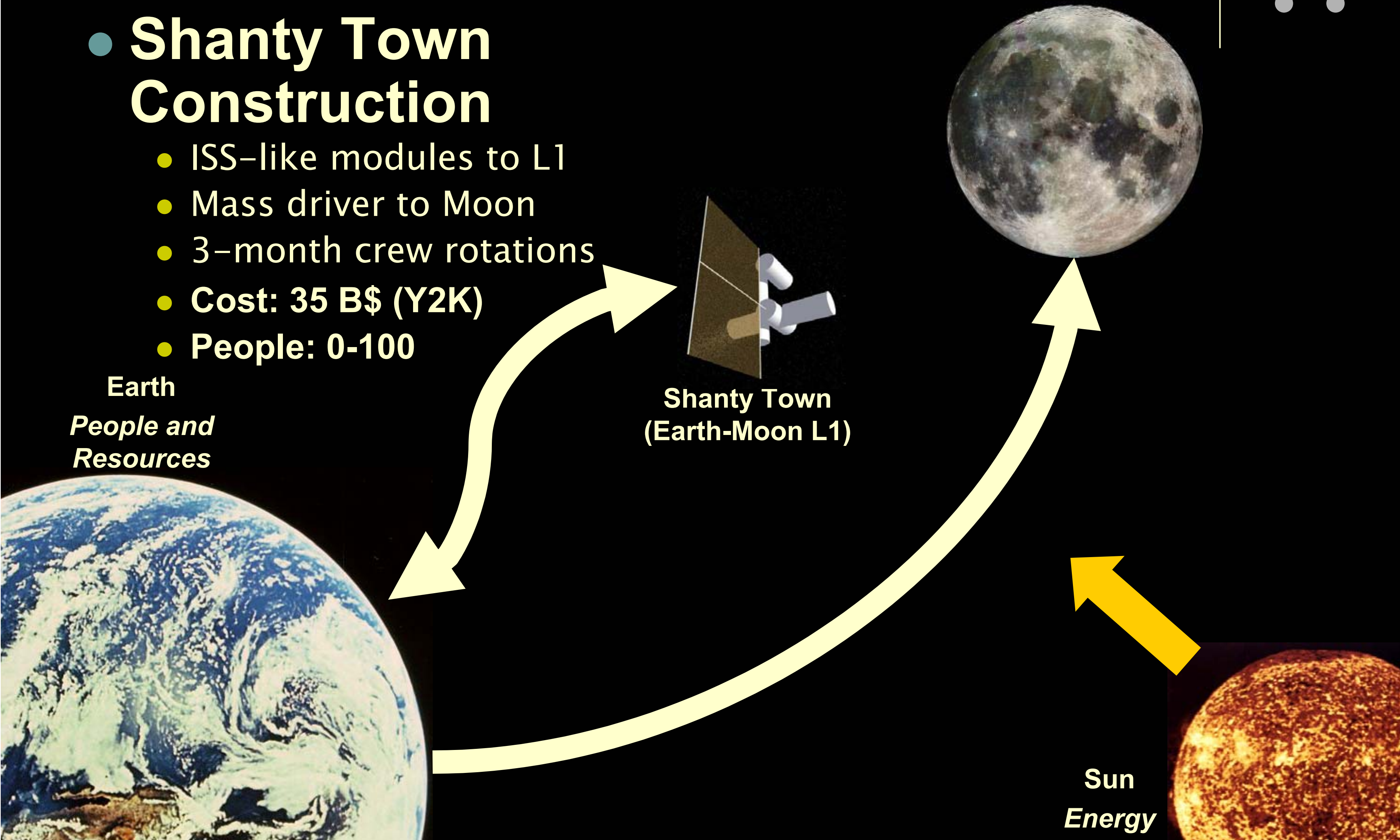
Launch Asteroid retrieval mission

Asteroid arrives at Heliopolis

Heliopolis construction begins; Lunar Mass Driver operational

Phase 0 (2020-2021)

- **Shanty Town Construction**
  - ISS-like modules to L1
  - Mass driver to Moon
  - 3-month crew rotations
  - **Cost: 35 B$ (Y2K)**
  - **People: 0-100**



Moon
Resources

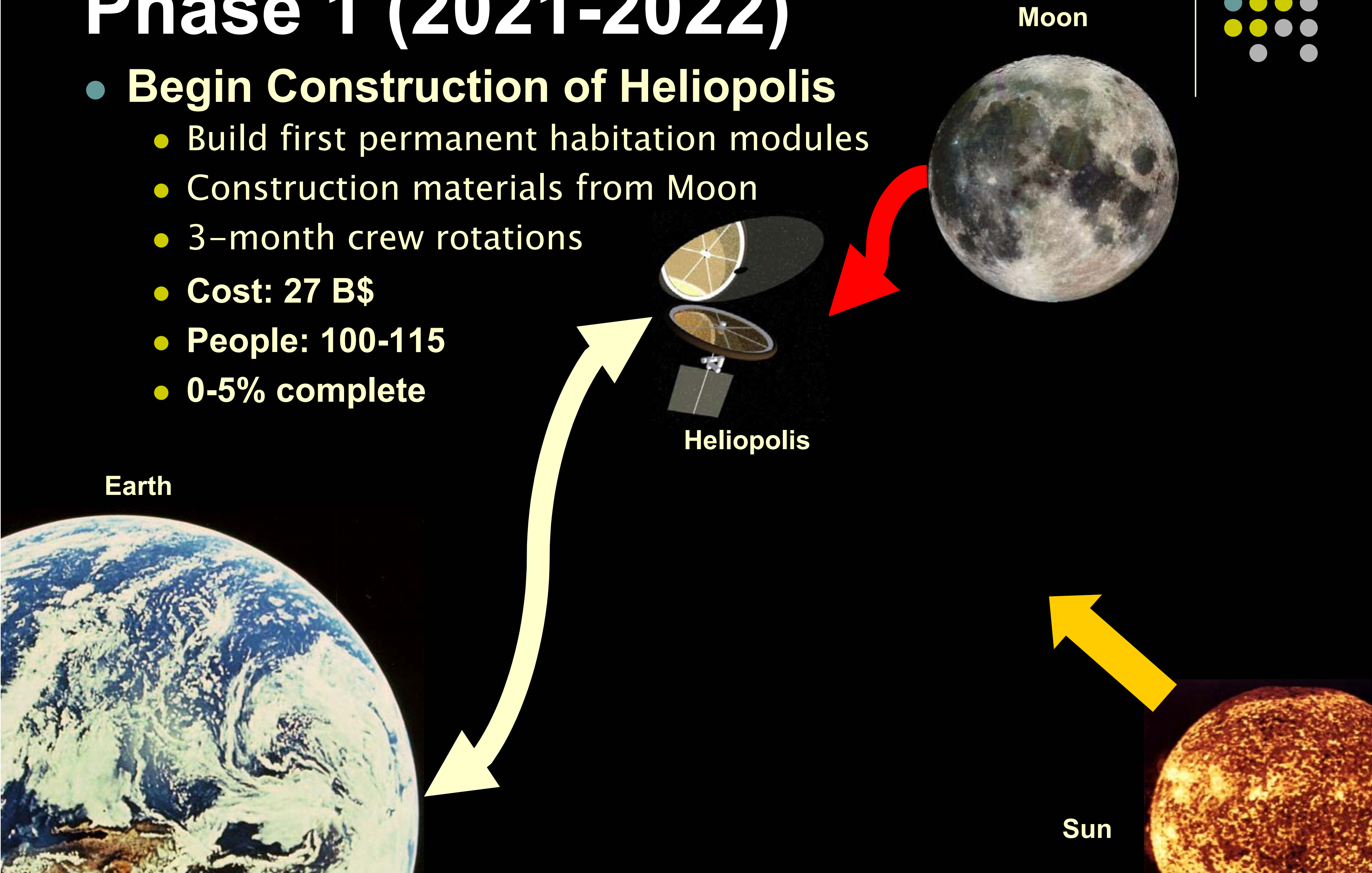
Earth
People and Resources

Shanty Town
(Earth-Moon L1)

Sun
Energy

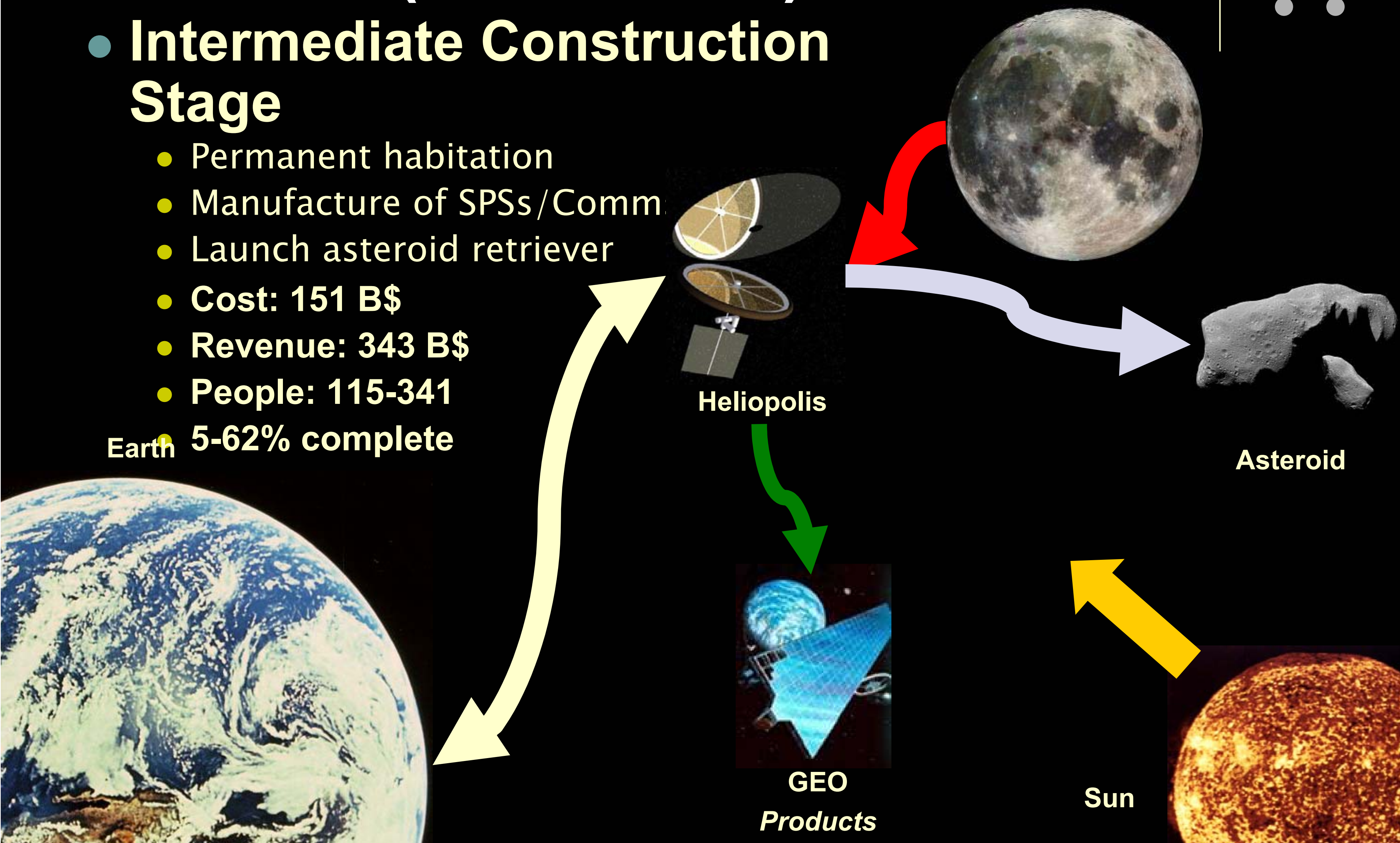
Phase 1 (2021-2022)

- **Begin Construction of Heliopolis**
  - Build first permanent habitation modules
  - Construction materials from Moon
  - 3-month crew rotations
  - **Cost: 27 B$**
  - **People: 100-115**
  - **0-5% complete**



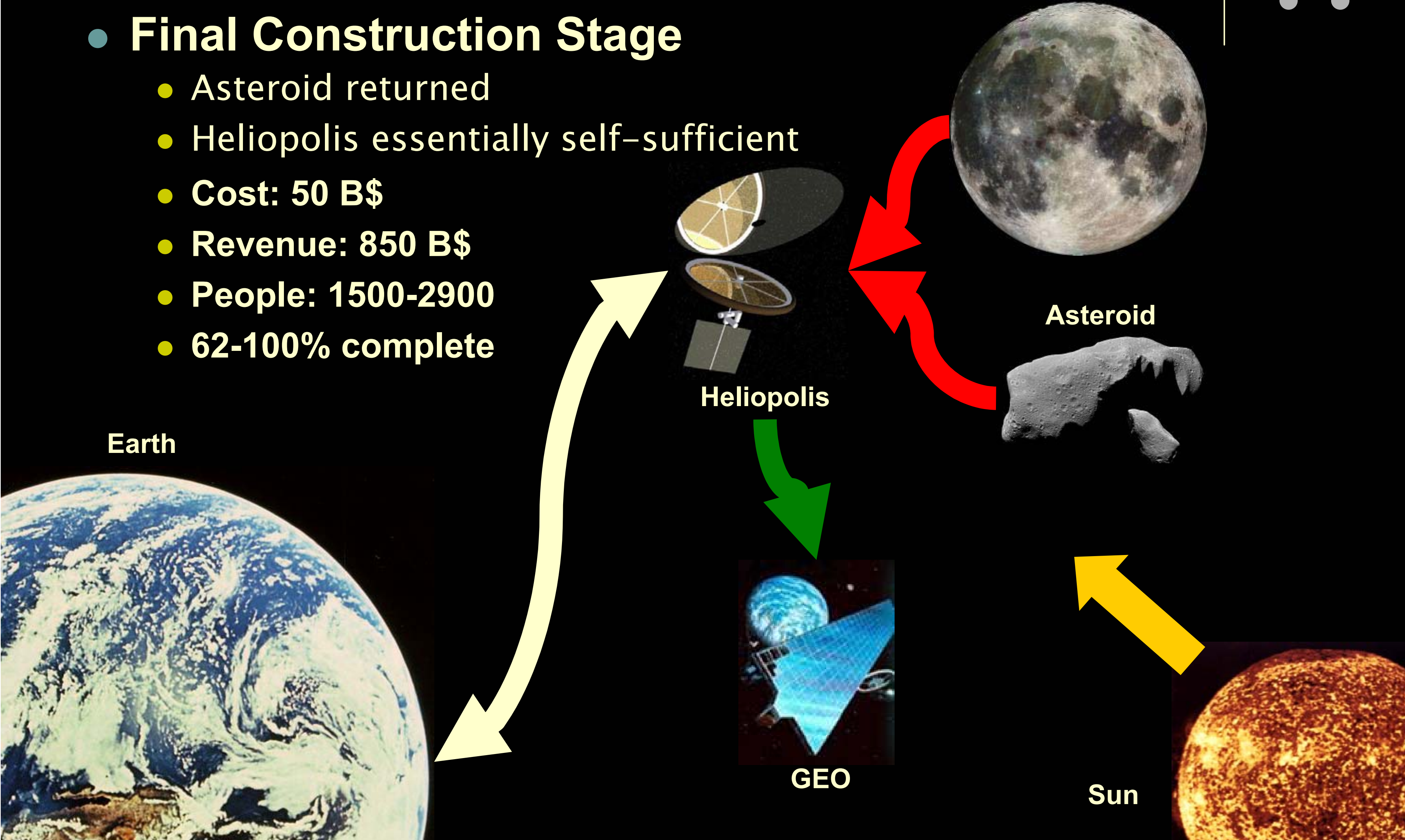
Phase 2 (2022-2032)

- **Intermediate Construction Stage**
  - Permanent habitation
  - Manufacture of SPSs/Comm
  - Launch asteroid retriever
  - **Cost: 151 B$**
  - **Revenue: 343 B$**
  - **People: 115-341**
  - **5-62% complete**



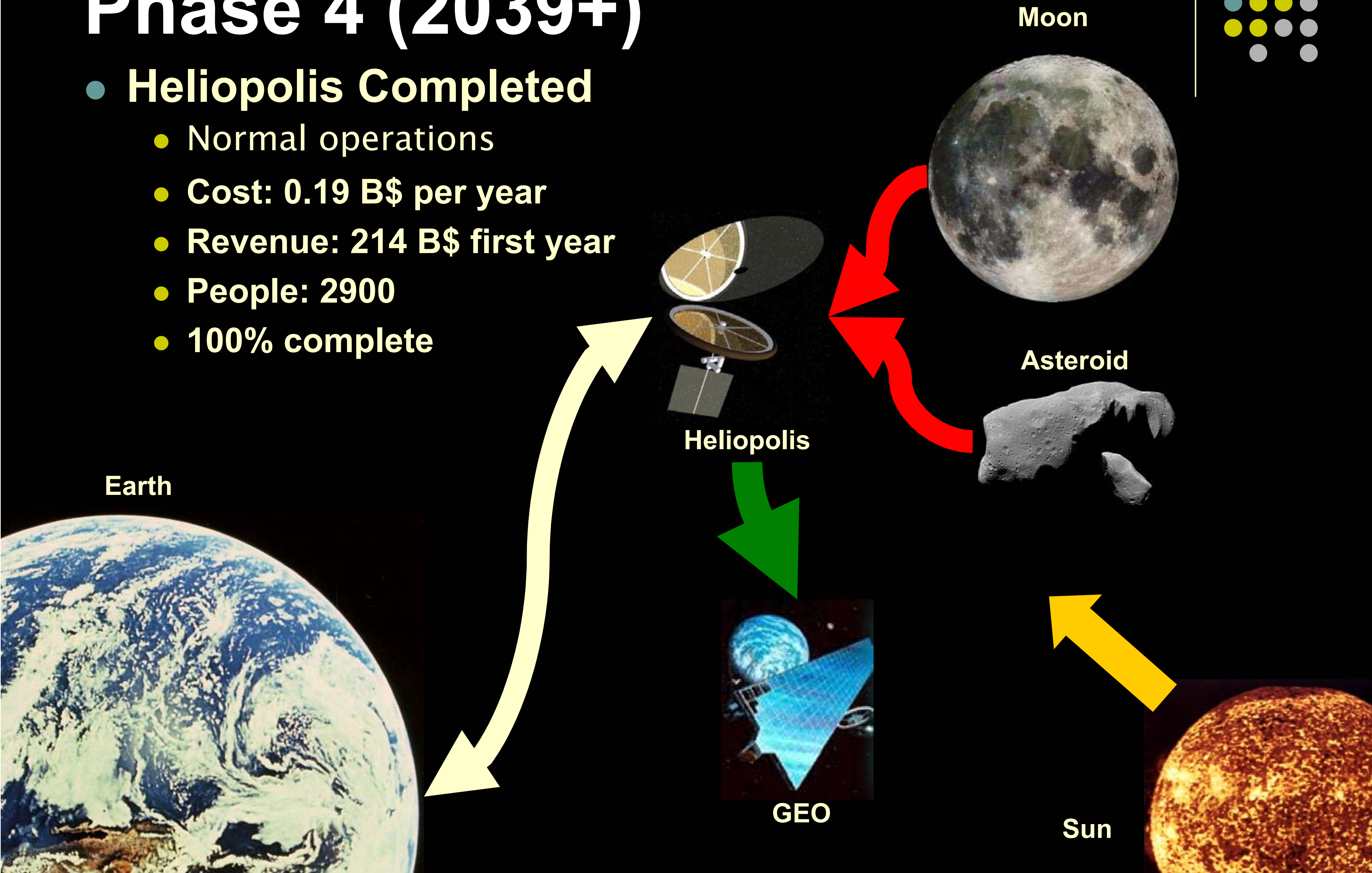
Phase 3 (2032-2039)

- **Final Construction Stage**
  - Asteroid returned
  - Heliopolis essentially self-sufficient
  - **Cost: 50 B$**
  - **Revenue: 850 B$**
  - **People: 1500-2900**
  - **62-100% complete**



Phase 4 (2039+)

- **Heliopolis Completed**
  - Normal operations
  - **Cost: 0.19 B$ per year**
  - **Revenue: 214 B$ first year**
  - **People: 2900**
  - **100% complete**



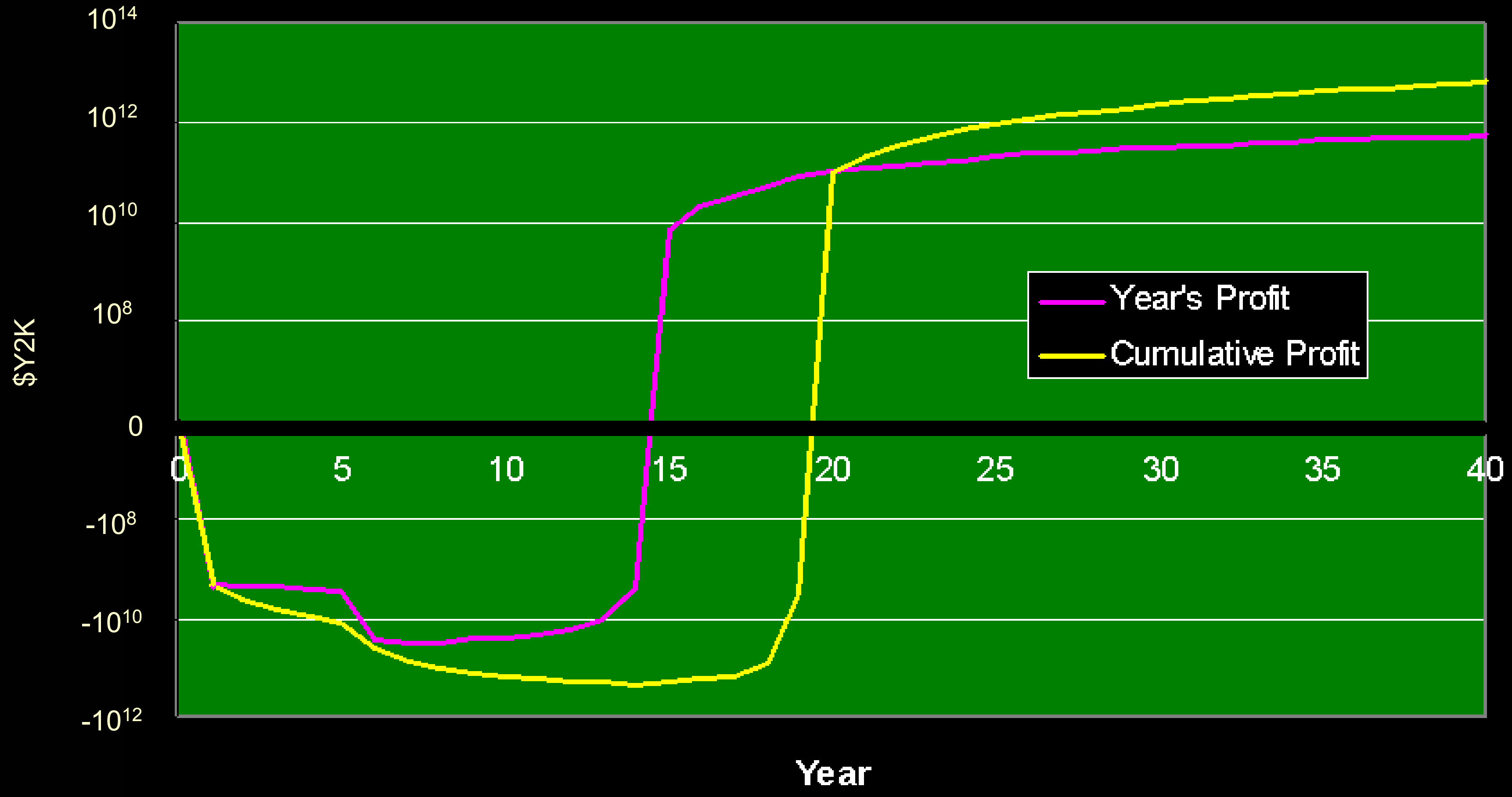
Infrastructure Requirements

- Module fabrication facility
- Heavy-lift launch vehicle (HLLV) services
- Lunar mass driver
- Inter-orbital shuttle
- Ground receiver arrays (rectennas)

Technology Requirements

- Enabling Technology
  - 250-tonne-to-LEO class HLLV
  - Improved automation
  - Nuclear reactor in space
  - Closed-loop recycling
- Enhancing Technology
  - SEP using O2
  - Nuclear thermal propulsion
  - Improved PowerSail efficiency
  - Mass driver propulsion
  - Self-Replicating Machines

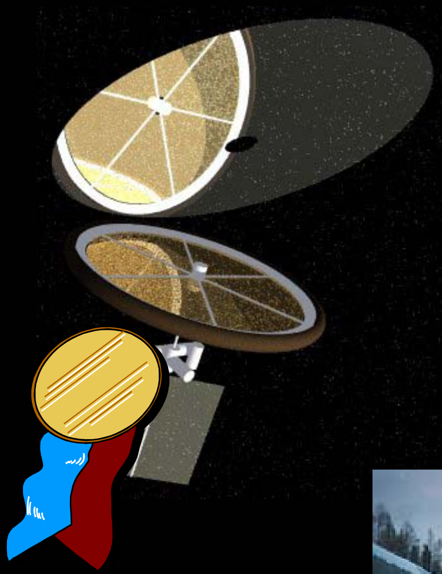
Cash Flow Analysis (log scale)

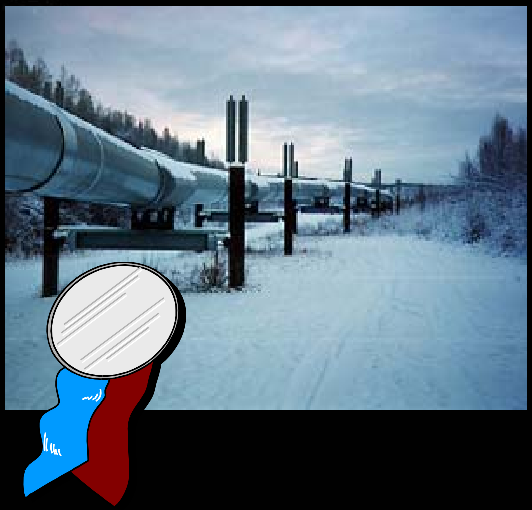


Chad

Alaska Pipeline Comparison

	Alaska Pipeline	Heliopolis
Cost before revenue	22.7 B$	105 B$
Time to revenue	2.21 years	15 years
Avg. cost per year before revenue	10.3 B$	7 B$
Avg. profit per year	3 B$	214 B$[1]
Energy supplied per year[2]	94.5 MBTUs delivered	233 MBTUs produced



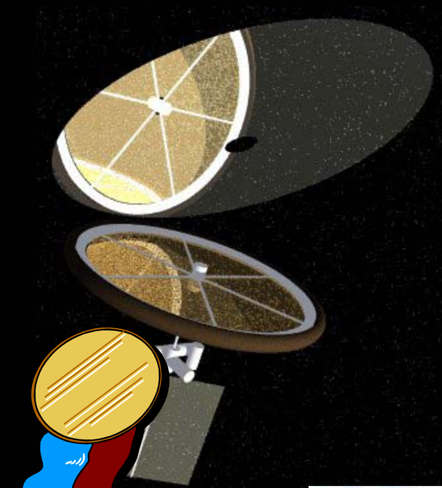


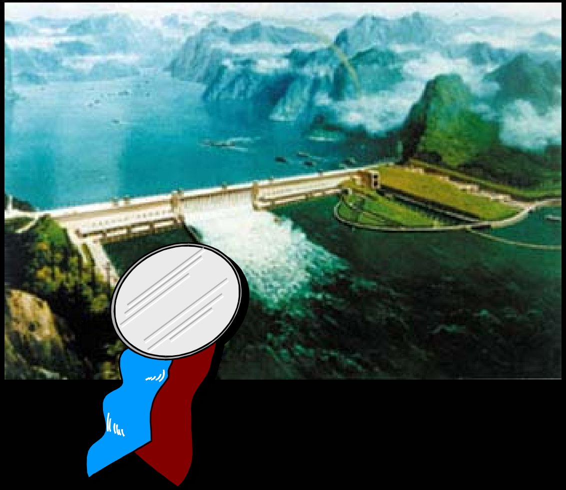
[1] Beginning of Phase 4

[2] World demand of 612 QBTUs in 2020

Three Gorges Dam Comparison

	Three Gorges Dam	Heliopolis
Cost before revenue	26.6 B$	105 B$
Time to revenue	20 years	15 years
Avg. cost per year before revenue	1.33 B$	7 B$
Avg. profit per year	62.8 B$[3]	214 B$[1]
Energy supplied per year[2]	0.54 MBTUs delivered	233 MBTUs produced





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[1] Beginning of Phase 4

[2] World demand of 612 QBTUs in 2020

[3] Revenue; profit figures unavailable

Environmental Impact

Alaska Pipeline	Three Gorges Dam	Nuclear Power	Heliopolis
12 M gallons of oil spilled over last 25 years	Toxic levels of arsenic, mercury, lead, cyanide in water supply; 1.9 million people displaced	Chernobyl affected 7 million, contaminated 155,000 sq.km[1]	Construction of rectennas (but still allows use of land); microwaves not harmful[2]

[1] Belarussian Embassy website
[2] 1975 Stanford study

Conclusions (1 of 3)

- O'Neill was right: world market exists to begin supply of solar energy
  - World demand of 612 QBTUs[1] far exceeds world production capability of 496 QBTUs[2]
  - SPS production can begin to supply unmet demand
- Solar energy from SPS cleaner, safer than alternatives
  - No risk of toxic wastes/spills
  - No risk of explosions or meltdowns
  - No people displaced, no land made unusable

[1] US DoE
[2] International Energy Agency

Conclusions (2 of 3)

- LSMD study comparable to 1975 Stanford study
  - Differences reflect 25 years of technological advances
- However: LSMD study represents fundamentally new analysis
  - Integrated cost model demonstrates project’s economic feasibility
- Technology exists or can be designed to begin project in the next 20 years

Conclusions (3 of 3)

- Economic profit returned in 20 years
  - Positive cash flow in 15 years
  - Initial investment of $105 billion
  - Self-sufficiency and internalizing costs critical to project success
- Power requirements dominated by industrial refinery needs
- Project cost driven by food production
  - Low mass, but biomass only available from Earth
  - Personnel costs surprisingly insignificant

Technical Study: Overview

- **Design Problems/Requirements & Solutions**
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Orbit Requirements & Options

- **Requirements**
  - **Fast and cheap access to**
    - ***Earth*** (employees, tourists)
    - ***Resources*** (Moon, near-Earth asteroids)
    - ***Market*** (geosynchronous orbit for SPSs)
  - **Continuous sunlight**
    - Dependent on solar energy
  - **Favorable to tourists**
  - **Favorable radiation environment**

- **Options**
  - Low Earth Orbit (ISS-like, LEO)
  - Sun-Synchronous Orbit
  - Highly Elliptical Earth Orbit
  - Geosynchronous orbit (GEO)
  - **Earth-Moon L1 halo orbit**

Earth-Moon L1 Orbit

- Advantages
  - Fast and cheap access to Resources and Market
    - Orbit outside Earth's deep potential well
    - *Resources:* Moon and NEAs are easy to access
    - *Market:* Less energy to GEO than from LEO[1] and less radiation damage to SPSs[2]
  - Continuous sunlight
    - Eclipses are rare, brief
  - Favorable to tourists
    - Earth and Moon views

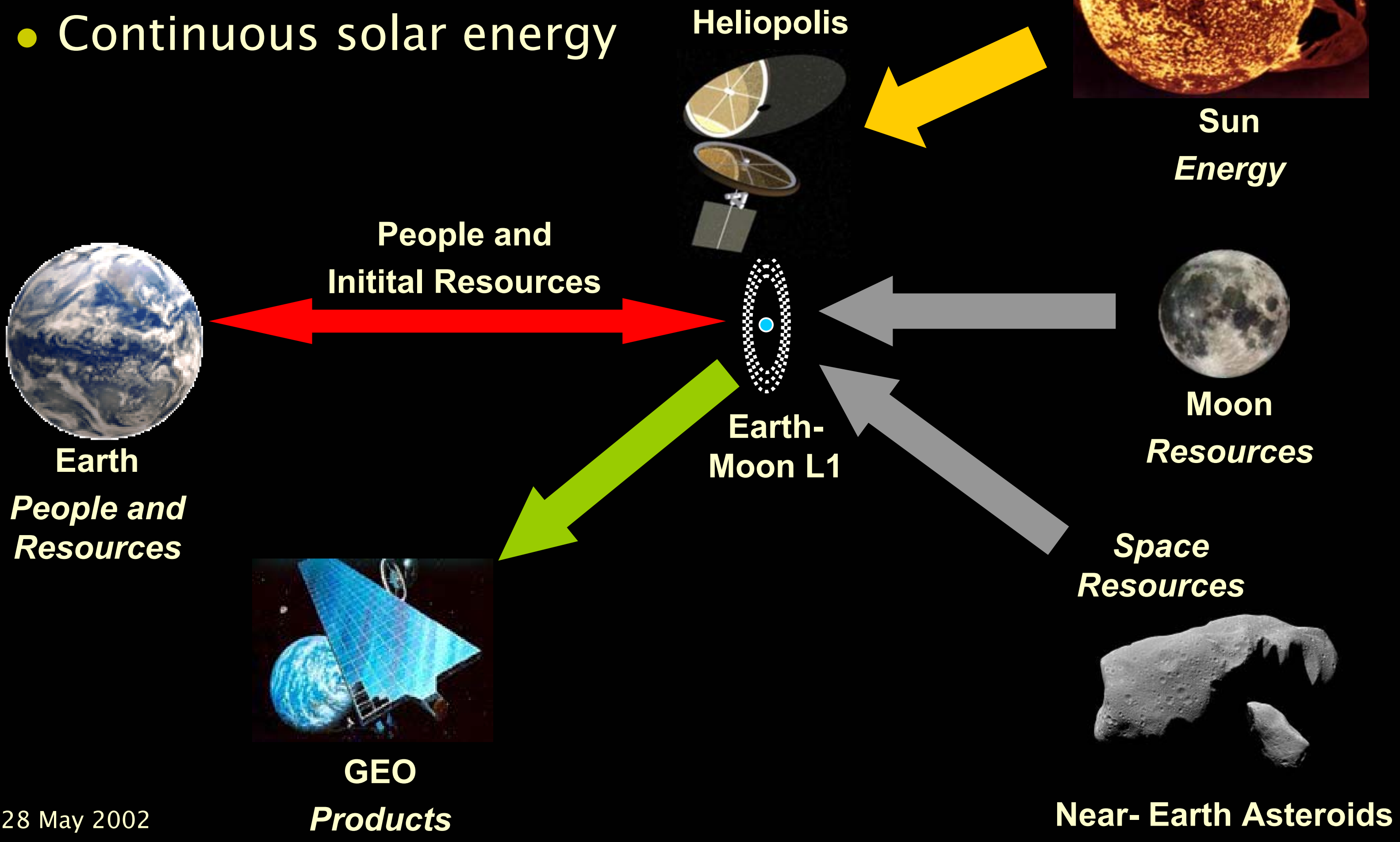
- Disadvantages
  - Far from Earth
    - *Earth:* Trip times of one to a few days to and from Earth
  - Radiation environment
    - Not protected by Earth's magnetic field

[1] Impulsive ΔV: 1.2 km/s (Ross [2002]) compared to 3.5 km/s (Lewis [1991])

[2] Traversing the Van Allen Belts between LEO and GEO can do great damage to SPSs, lowering the efficiency of solar panels by upwards of 50%; L1 is beyond the Van Allen Belts

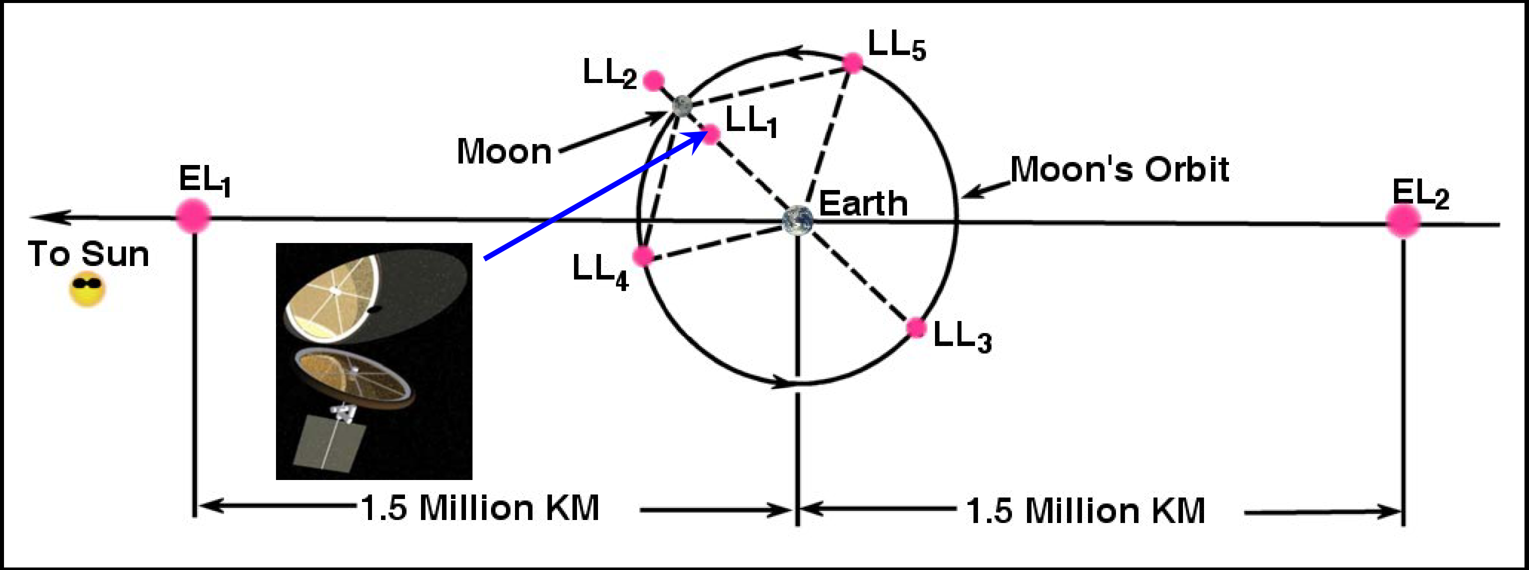
Earth-Moon L1 Orbit Selected

- Near Moon and NEA resources
- Goods cheaply sent to GEO
- Continuous solar energy



Space Highways

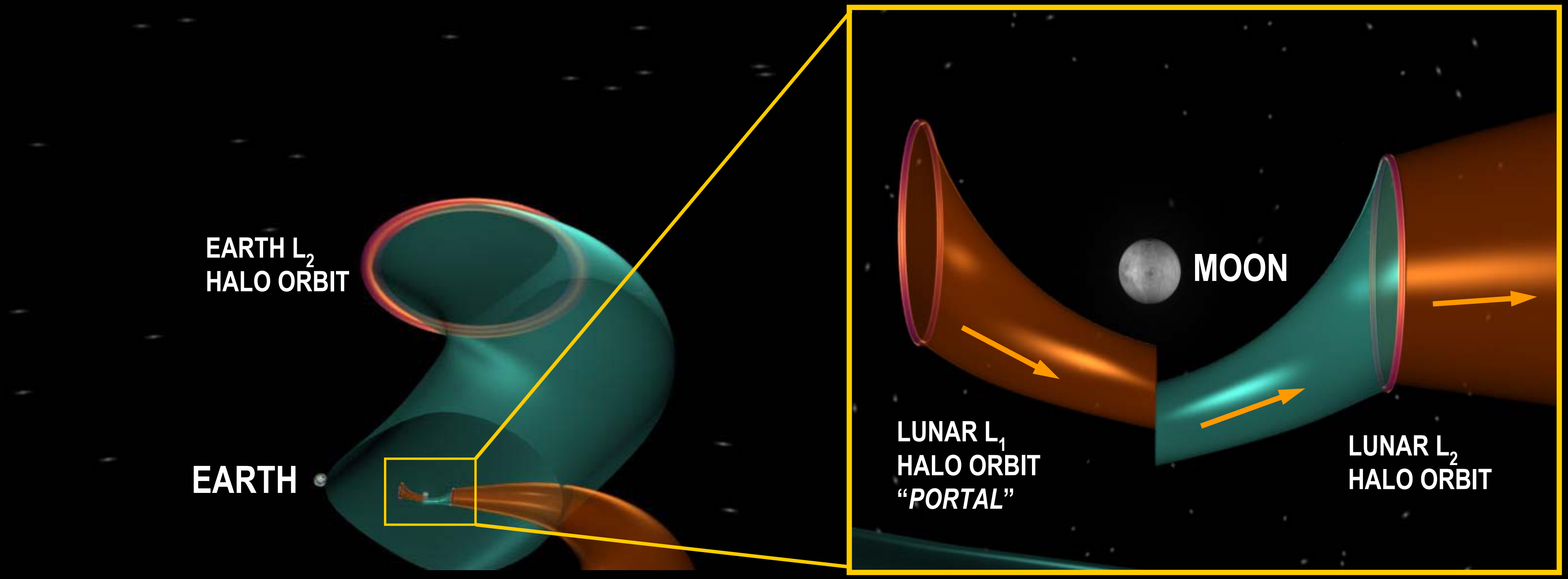
- **From L1, can access the InterPlanetary Superhighway**
  - Low fuel transfers to/from Earth-Moon space
  - Uses natural pathways connecting Lagrange points in Sun-Earth-Moon system



M.W. Lo and S.D. Ross [2001] The Lunar L1 Gateway: Portal to the Stars and Beyond. *AIAA Space 2001 Conference, Albequerque, New Mexico, 2001* (after Farquhar [1977]).

Space Highways

- **Earth-Moon L1 Halo Orbit "Portal"**
  - Low fuel access to lunar orbit, Earth orbit, and beyond
  - Near-Earth asteroid retrieval



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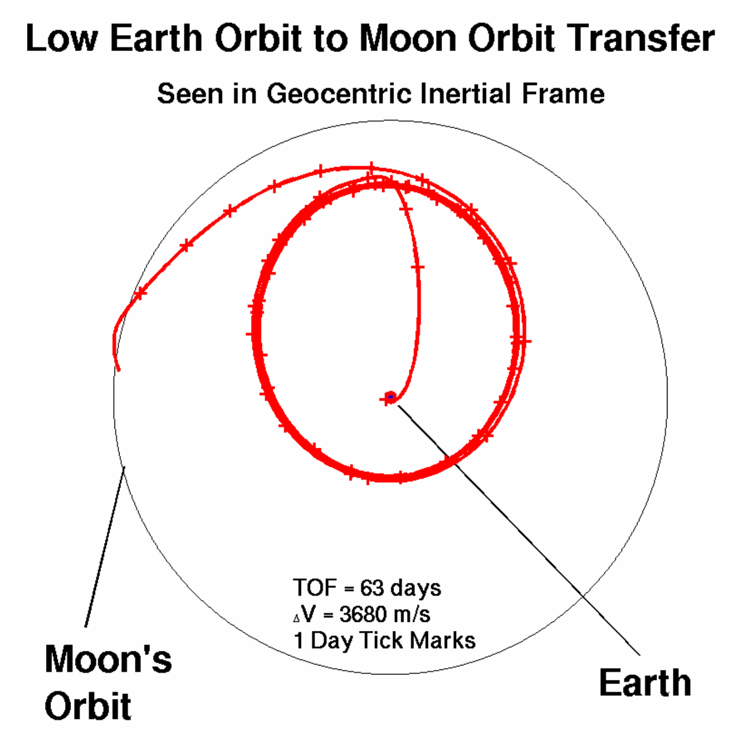
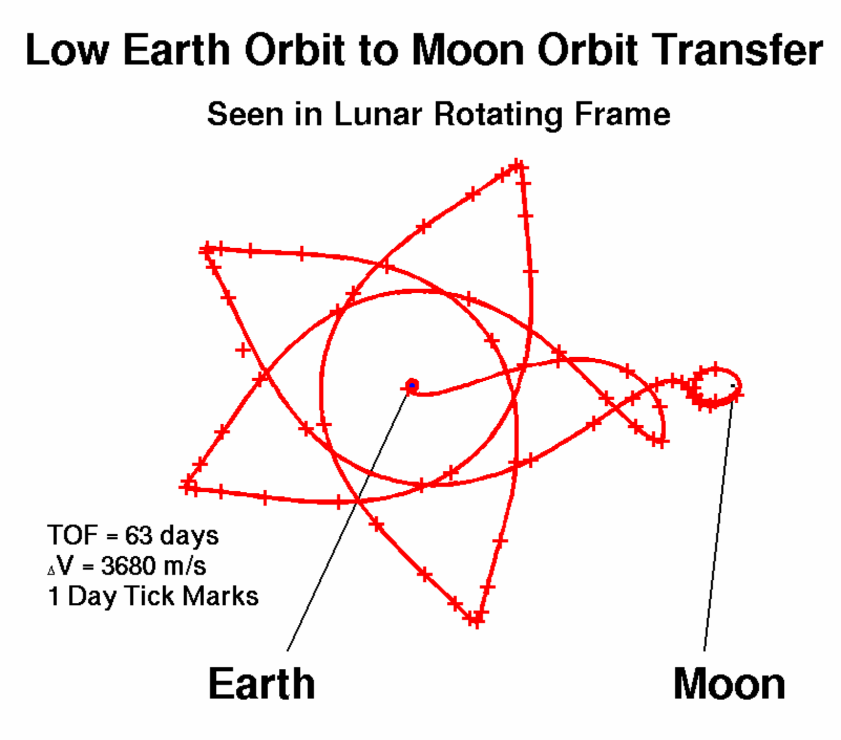
Space Highways

- **LEO to Earth-Moon L1**
  - Expends 30% less on-board fuel than a Hohmann transfer

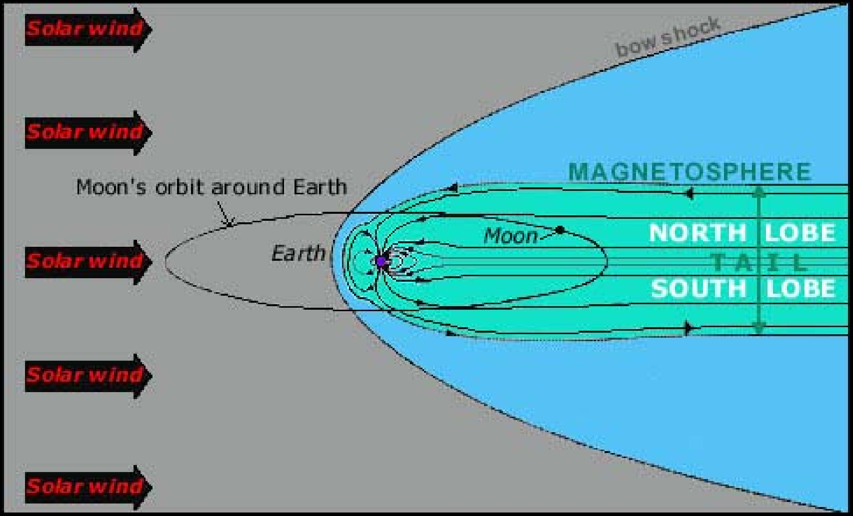




Ross, S. D. [2002] Low energy transfers to the moon using resonance targeting, *in preparation.*

Radiation Environment

- Earth-Moon L1
    - Not protected by Earth's magnetic field
    - Mostly unidirectional field of solar cosmic rays
        - High energy (1 GeV) protons, electrons, and heavy nuclei
- Significant shielding necessary
    - 12 cm Aluminum[1]
    - Slag from refining => thick shielding[2] (~ 2 m)



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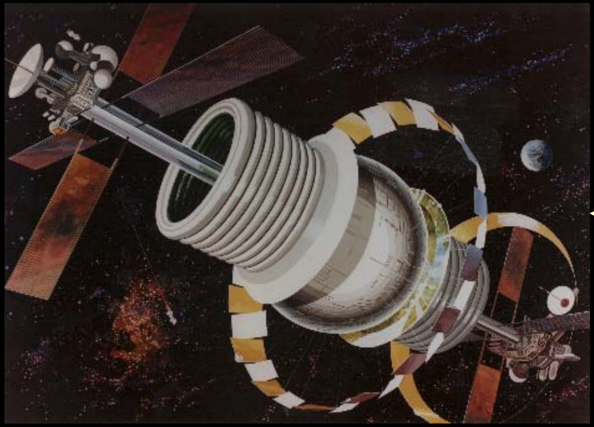
[1] Adapted from Tascione [1994], assuming shielding proportional to exp(-t), where t is shield thickness and keeping dose below 0.25 rem/year

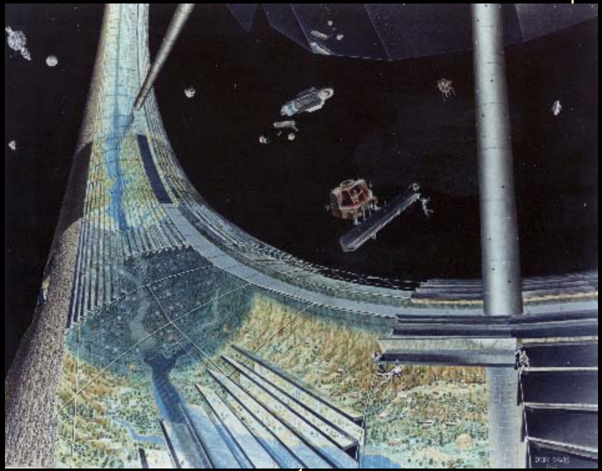
[2] Assuming slag from refining has the same shielding ability as lunar regolith

Structure Requirements (1 of 3)

- Human physiology → artificial gravity → rotation
- Human physiology → slow rotation
- Major radius 894m creates 1g at 1rpm
- Rotating environment → axial symmetry
- Options (see next slide):
  - Sphere
  - Cylinder
  - Torus

Structure Requirements: (2 of 3)





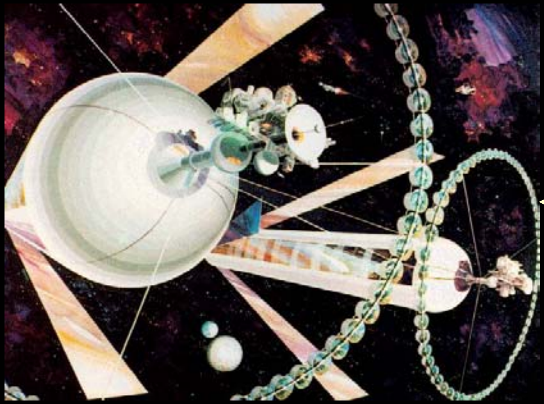
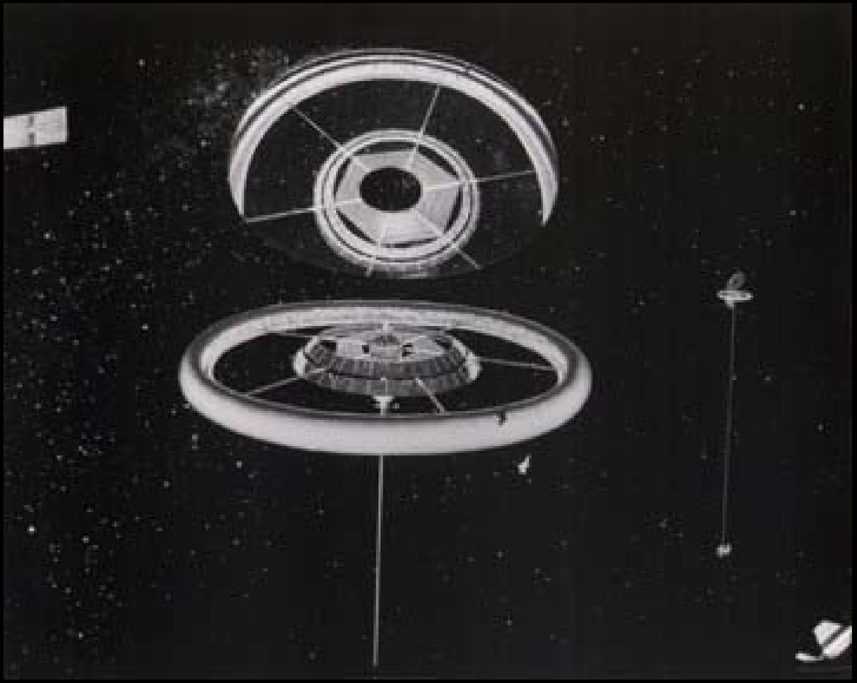


Image credit: NASA Ames

Image credit: SSI

Structure Requirements: (3 of 3)

- Minimum construction time → minimum structural material for required area, volume
- Radiation shielding requirements → minimum projected area
- Torus best satisfies requirements



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Initial Construction Phase: Requirements

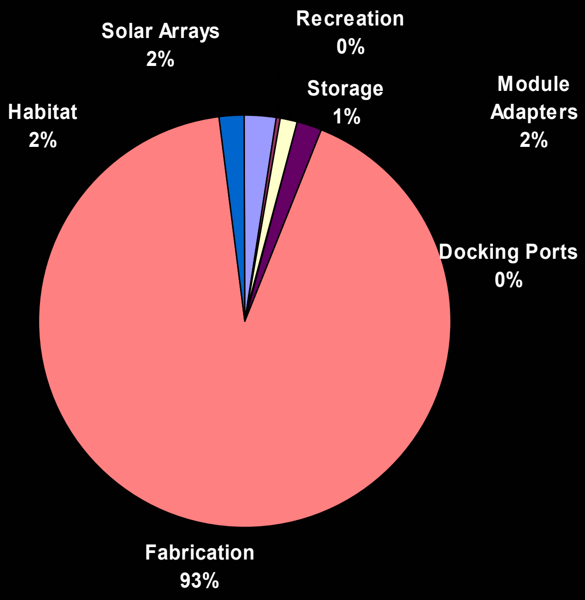
- Earth-built, Earth-launched components
- Minimum time to first launch
- Minimum development cost
- Facility must be at L1
  - Need a HLLV[1] capable of launching to this altitude
- Solution: “Shanty Town” (see next slide)

[1] Heavy-Lift Launch Vehicle

Shanty Town: Overview

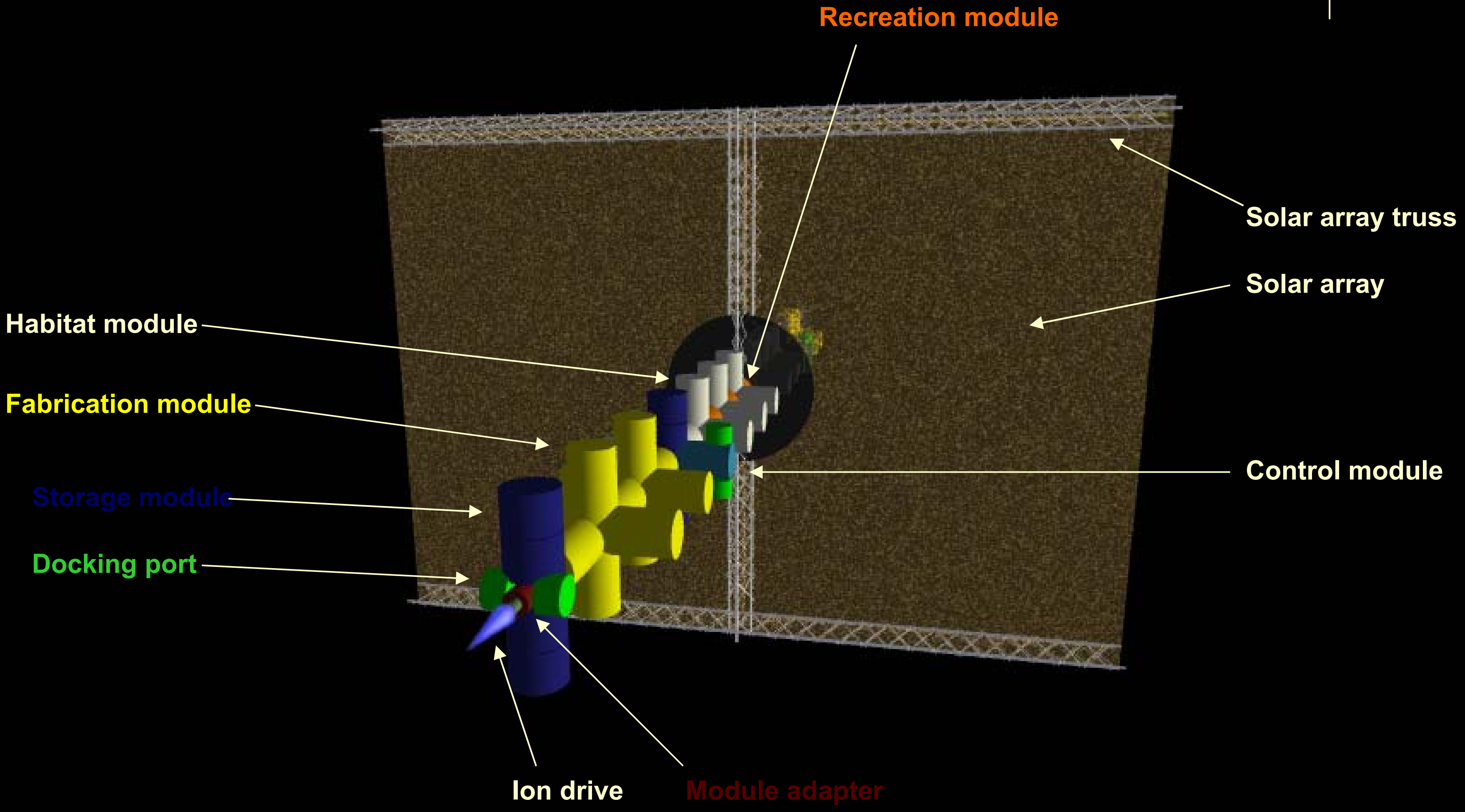
- Assembled primarily from build-to-print ISS modules
- ~100 people inhabit 17 “Zvezda” style modules
- 63 fabrication modules begin construction of Heliopolis
- 25 connectors, 50 storage modules, 8 docking ports, and 3 “recreation” modules complete the station

Shanty Town Mass Breakdown



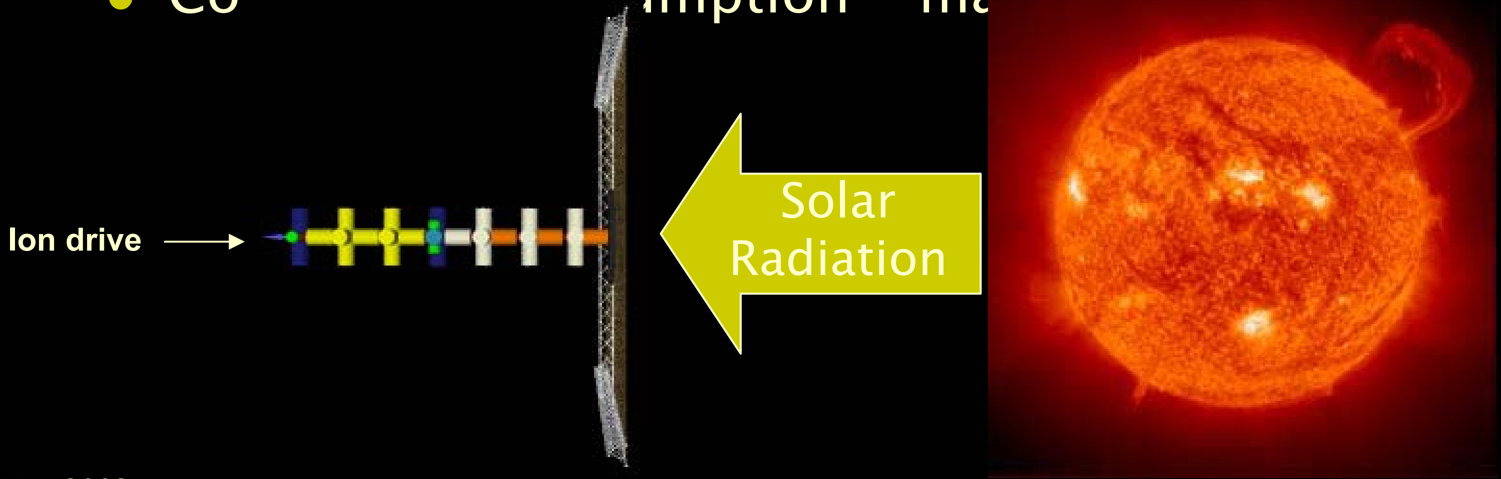
Total Mass 16,760 tonnes

Shanty Town: Layout



Shanty Town: Positioning

- Orbit at L1 maintained so that radiation is essentially unidirectional
  - Symmetric positioning of station eliminates solar radiation torque; solar array creates large solar radiation force
  - Ion drive used to counteract radiation force
    - Conservative assumption – may not be required



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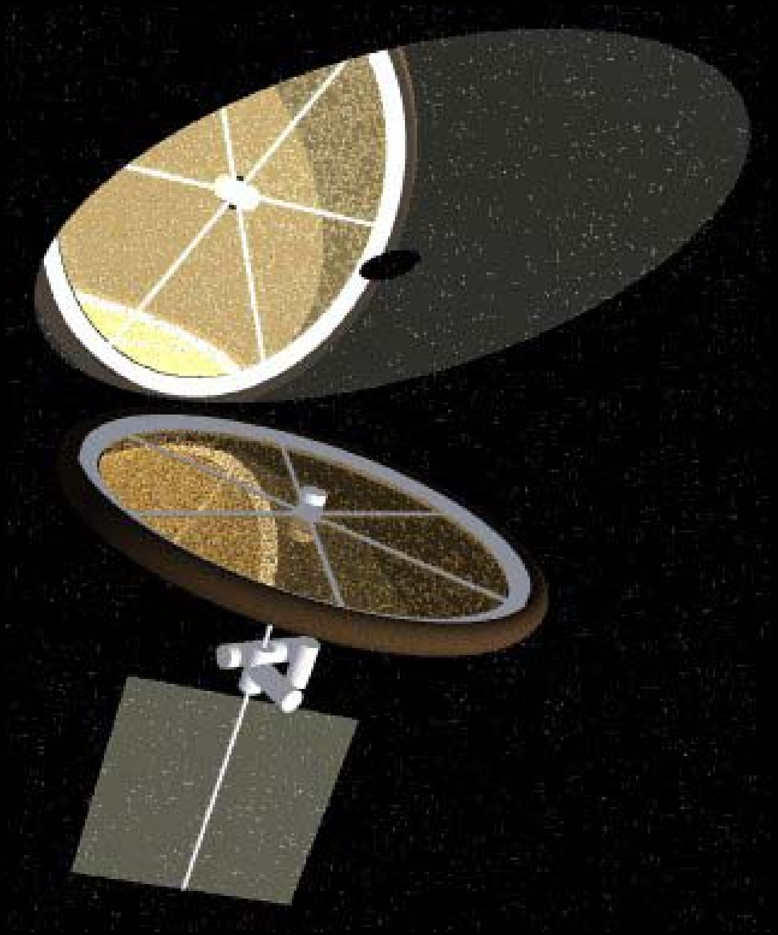
Heliopolis



- Toroid structure of double-walled aluminum
- Material largely extraterrestrial
- 20 years to build
- 894.3m (r_o) x 36m (r_i)
  4.1M m^3 internal volume
  212,000 tonnes total mass

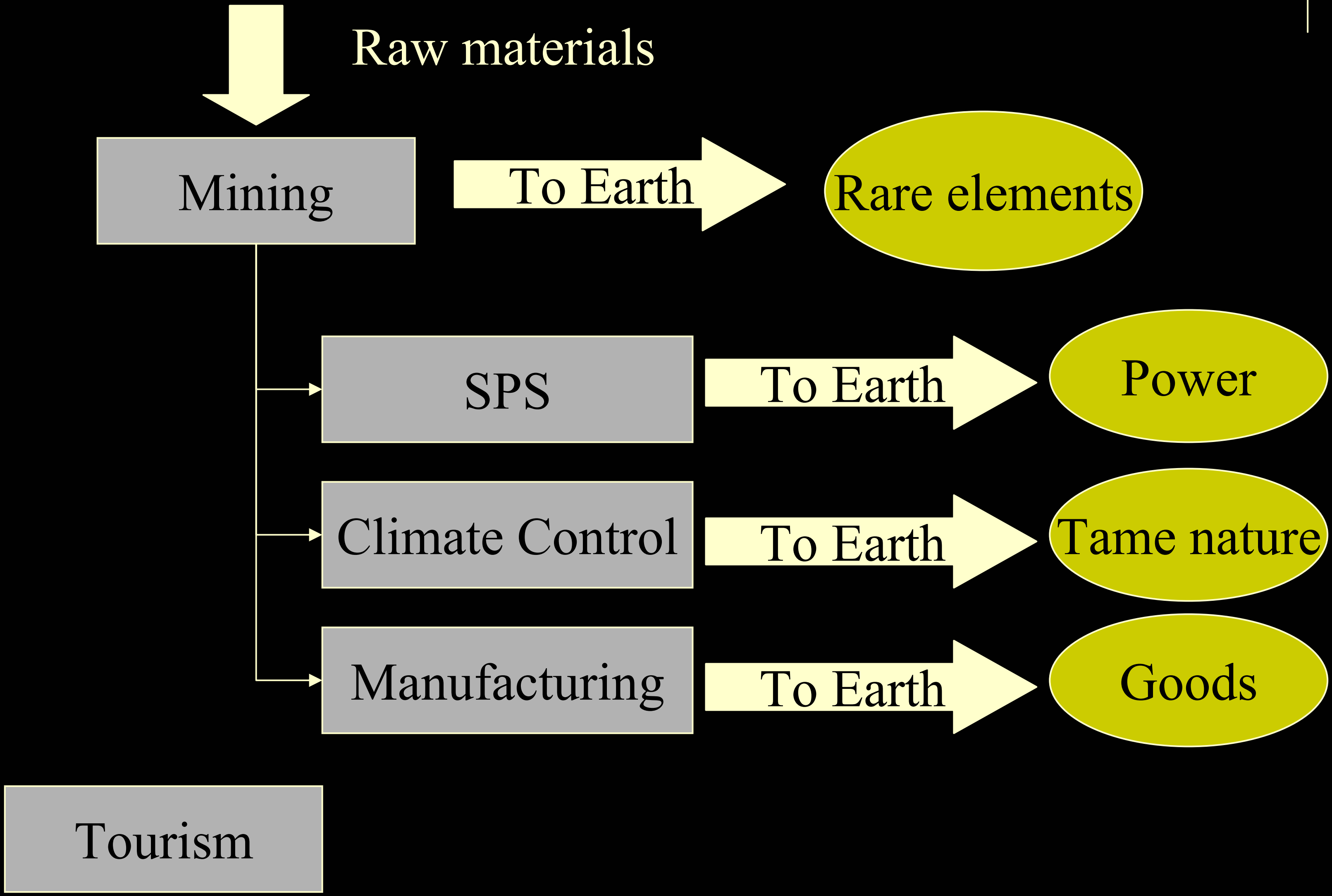
Heliopolis (cont.)

- Self-sufficient (except for limited specific goods)
- Construction platform for Earth-orbit and extraterrestrial consumption
- Staging post for deep space missions

Industrial-Tourist Complex

- The industries were selected for their economic feasibility, usefulness, and ease of integration with the space colony’s goals and purpose
- Asteroid Mining – Provides raw materials for colony construction and space undertakings, and rare metals as cash crop for Earth
- Manufacturing – Initially directed towards station construction; later produces consumer goods for use in space, or exotic goods for export to Earth
- SPS, Climate Control – Uses assembly bays and raw materials required for colony construction and returns power and productive climate to Earth
- Tourism – Habitat for colony workers doubles as a recreational hotel with scenic excursions to the industry facilities and into space

Industry Interdependencies



Raw materials

Mining

To Earth

Rare elements

SPS

To Earth

Power

Climate Control

To Earth

Tame nature

Manufacturing

To Earth

Goods

Tourism

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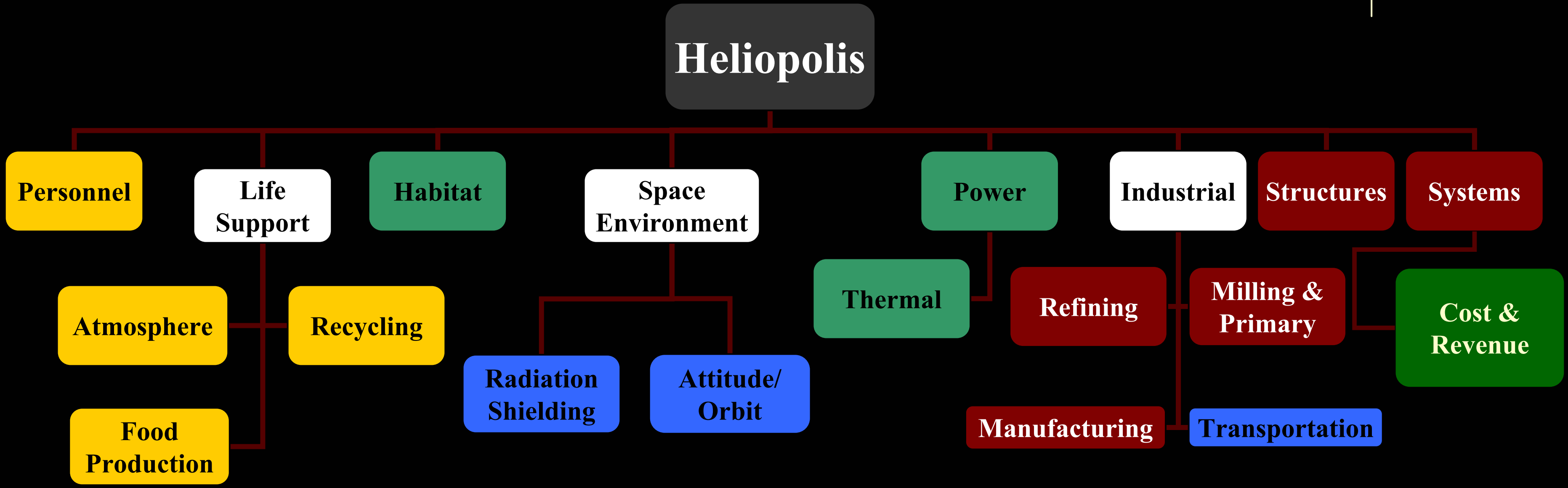
Functional/Work Decomposition



Heliopolis

- Personnel
- Life Support
  - Atmosphere
  - Recycling
  - Food Production
- Habitat
- Space Environment
  - Radiation Shielding
  - Attitude/ Orbit
- Power
  - Thermal
- Industrial
  - Refining
  - Milling & Primary
  - Manufacturing
  - Transportation
- Structures
- Systems
  - Cost & Revenue

● Luke

● Melahn

● Ryan

● Shane

● Chad

○ Not represented as a model

Model Interface

- Models exchange a set of parameters among themselves
- Represented graphically for rapid understanding
- Approximately 515 exchange parameters (see next chart)

Data Transfer Matrix:

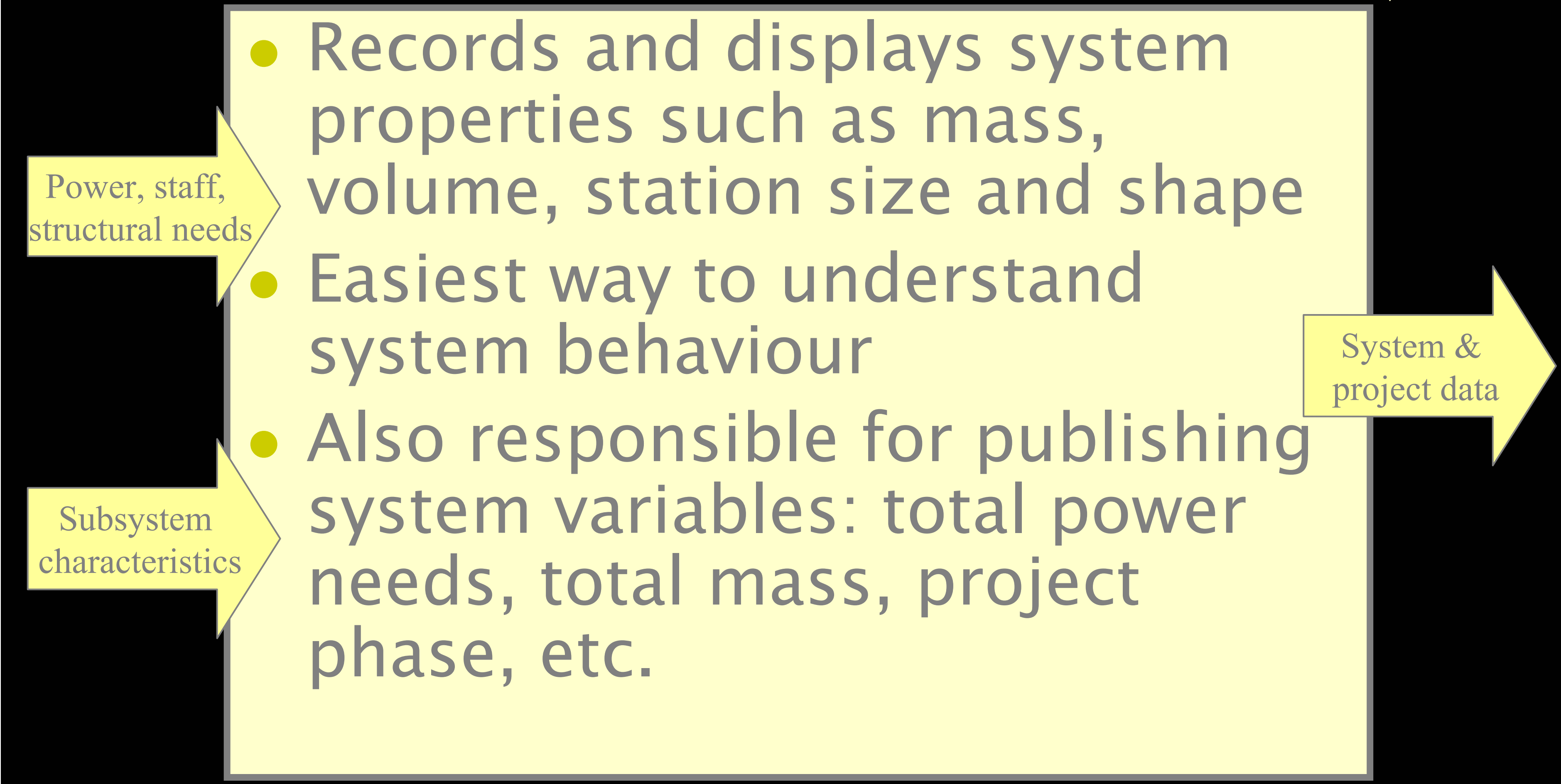
Parameters Passed Between Models

	Atmosphere	Attitude & Orbit	Cost	Food Production	Habitat	Manufacturing	Milling & Primary	Personnel	Power	Radiation Shielding	Recycling	Refining	Structures	Systems	Thermal	Transportation
Atmosphere	na	-	3	-	-	-	-	1	2	-	5	-	9	4	2	1
Attitude & Orbit	-	na	2	-	-	-	-	1	3	1	-	-	8	4	3	3
Cost	-	-	na	-	-	6	-	-	-	-	-	-	-	-	-	6
Food Production	8	-	7	na	-	-	-	1	2	-	3	-	8	4	2	4
Habitat	1	-	-	-	na	1	1	-	2	-	2	-	11	1	2	-
Manufacturing	-	-	3	-	-	na	8	1	3	-	2	1	17	5	2	1
Milling & Primary	-	-	1	-	-	9	na	1	3	-	2	22	12	5	2	-
Personnel	13	1	4	6	1	1	2	na	2	1	4	2	11	5	2	3
Power	-	-	3	-	-	-	-	1	na	-	-	-	14	7	2	-
Radiation Shielding	-	1	-	-	-	-	-	1	-	na	-	-	9	2	-	-
Recycling	4	-	-	1	-	-	2	1	2	-	na	-	8	4	2	-
Refining	-	1	2	-	-	2	13	1	3	2	-	na	11	5	2	1
Structures	1	11	21	-	-	3	1	1	2	7	1	-	na	21	2	2
Systems	1	9	11	1	1	8	5	1	3	4	1	5	10	na	1	9
Thermal	-	-	-	-	-	-	-	1	2	-	-	-	15	4	na	-
Transportation	-	-	3	-	-	-	-	1	2	-	-	1	8	5	2	na

Inputs from

Outputs to

Systems Model



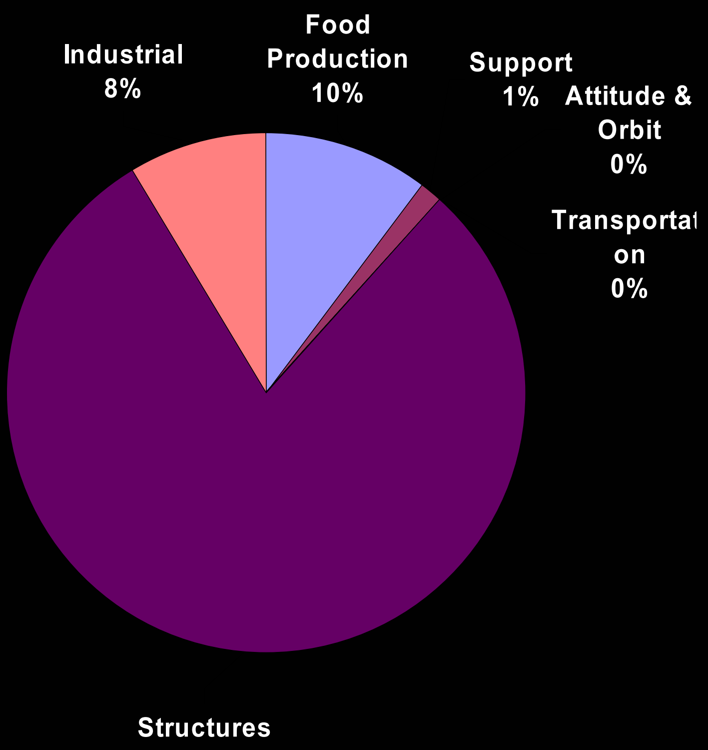
Power, staff, structural needs

Subsystem characteristics

- Records and displays system properties such as mass, volume, station size and shape
- Easiest way to understand system behaviour
- Also responsible for publishing system variables: total power needs, total mass, project phase, etc.

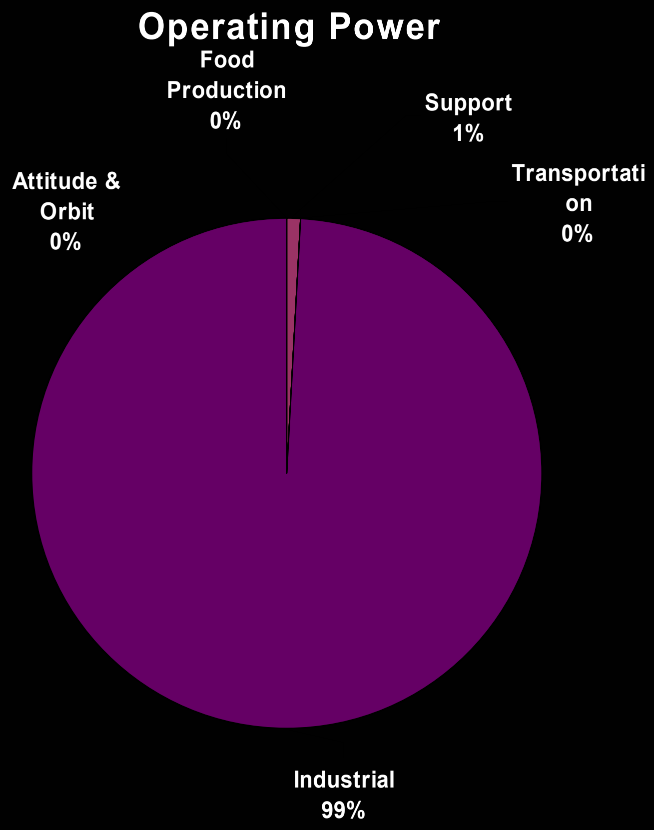
System & project data

Systems (cont.)


Mass Breakdown: Station

TOTAL	**212678**	**tonnes**
Food Production	21718	tonnes
Support	3080	tonnes
Atmosphere	2818	tonnes
Habitat	2	tonnes
Personnel	210	tonnes
Recycling	49	tonnes
Attitude & Orbit	5	tonnes
Transportation	100	tonnes
Structures	169698	tonnes
Industrial	18078	tonnes
Manufacturing	10909	tonnes
Milling & Primary	381	tonnes
Refining	6433	tonnes
Power	129	tonnes
Thermal	225	tonnes

Systems (cont.)



TOTAL	**440.702**	**MW**
Food Production	0.386	MW
Support	3.702	MW
Atmosphere	0.684	MW
Habitat	2.500	MW
Recycling	0.518	MW
Attitude & Orbit	0.029	MW
Transportation	0.000	MW
Industrial	436.585	MW
Manufacturing	30.894	MW
Milling & Primary	8.012	MW
Refining	397.679	MW

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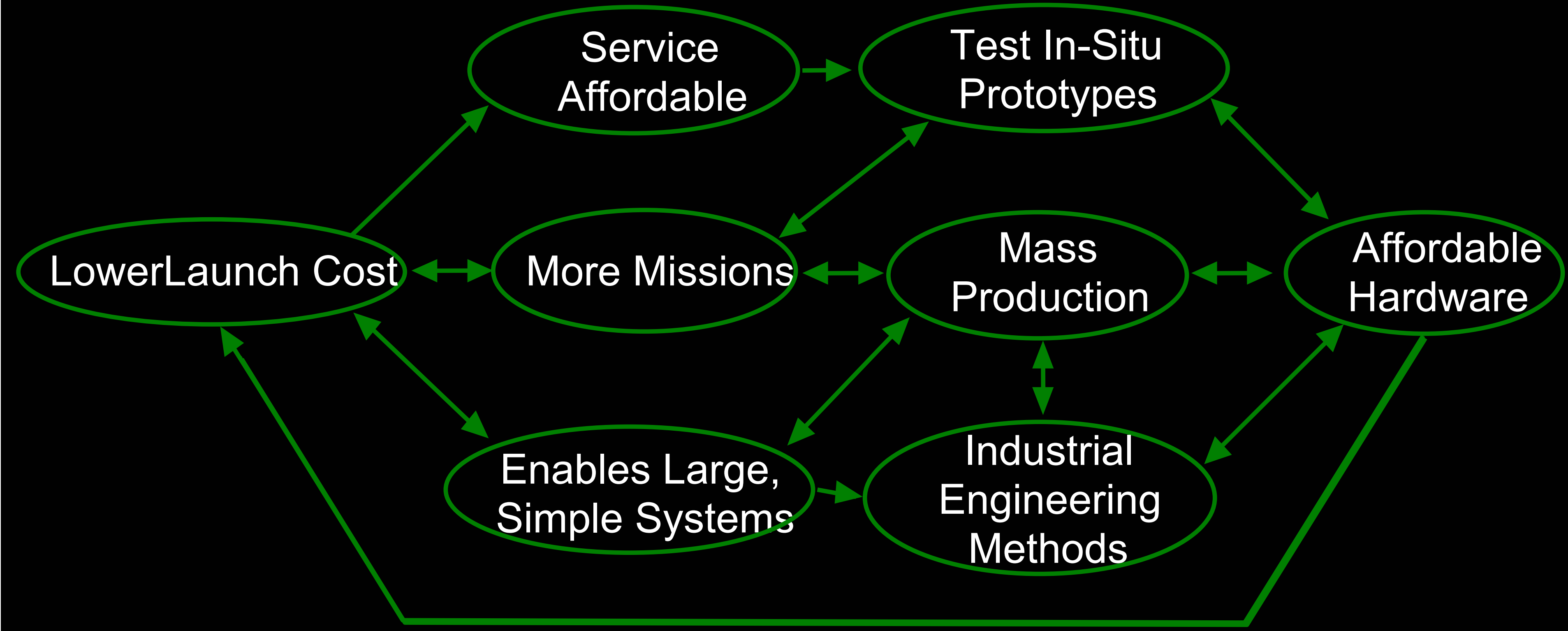
Cost Assumptions – Phase (-1)

- Phase (–1) – Research, Development, Design, and Testing
  - Start Date: 2015
  - Duration: 5 years
  - RDT&E = TFU * ICM * Launch Service Scalar
    - Assume most modules will be built to ISS specs
      - Habitat, Adapter, Communications, Storage, Docking
      - Theoretical First Unit (TFU) cost small
      - Initial Cost Multiplier (ICM) also small – using existing technology
    - Other modules scale as ratio of mass to ISS Habitat Module
      - Recreation, Fabrication
    - Assume TFU for Heliopolis is First Livable Section
      - Calculate TFU cost as cost of ISS scaled by mass ratio
    - Assume development cost scales with launch cost
      - Reliability less important because easier to fix problems
      - Mass less of a design concern

Hypothesized Effect of Launch Cost Reduction on Hardware Cost



See notes for reference

Cost Assumptions – Phase (-1)

- Assume Technological Advances
  - Ground Fabrication Plants can keep up with module production demand
  - Launch Services can keep up with launch demand
  - Total Cost of Phase (-1): **$8.83B**
- No Revenue Generated
- Assume Government guarantees investment
  - Interest Rate = 10%

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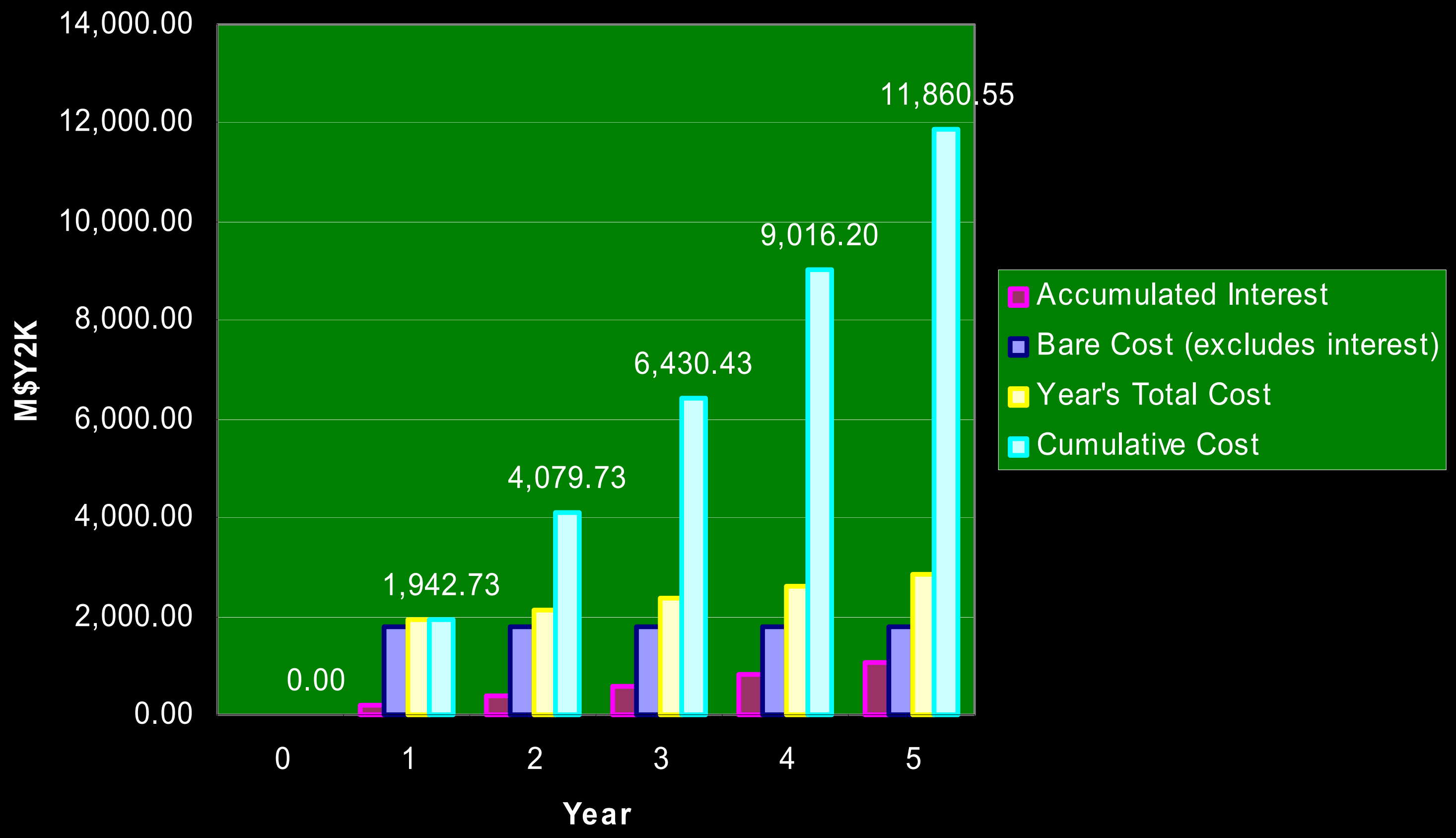
Cost – Phase (-1)

- Assume total phase cost evenly distributed amongst years of phase



28 May 2002

Cost Assumptions – Phase (0)

- Phase (0) – Construction of Shanty Town & Lunar Mining Plant
  - Assume cost of Lunar Mining Plant is correctly estimated by O'neill, and inflate to M$Y2K
    - Total Lunar Mining Plant Cost = $8,884.2M
  - Cost of phase driven by module construction and launch services
    - Assume launch services to L1 cost $2,000 / kg in 2020
      - Independent developer creates NOVA-class vehicle technology capable of launching 250 tonnes to L1
      - Lower launch service cost decreases cost of construction (see slides 48, 49)
    - Assume a learning curve for the mass production of modules

Cost Assumptions – Phase (0)

- Learning Curve formula[1]
  - X = # of modules to be built
  - S = Learning Curve slope (%)
    - 95 if (x < 10)
    - 90 if (10 <= x <= 50)
    - 85 if (x > 50)
  - B = 1 – ln(100%/S) / ln(2)
  - L = Learning Curve Factor = X ^ B
    - Effective number of units at full TFU cost
  - Production cost = TFU cost * L

---

[1] Method from Space Mission Analysis and Design (SMAD) by Wertz & Larson 1999

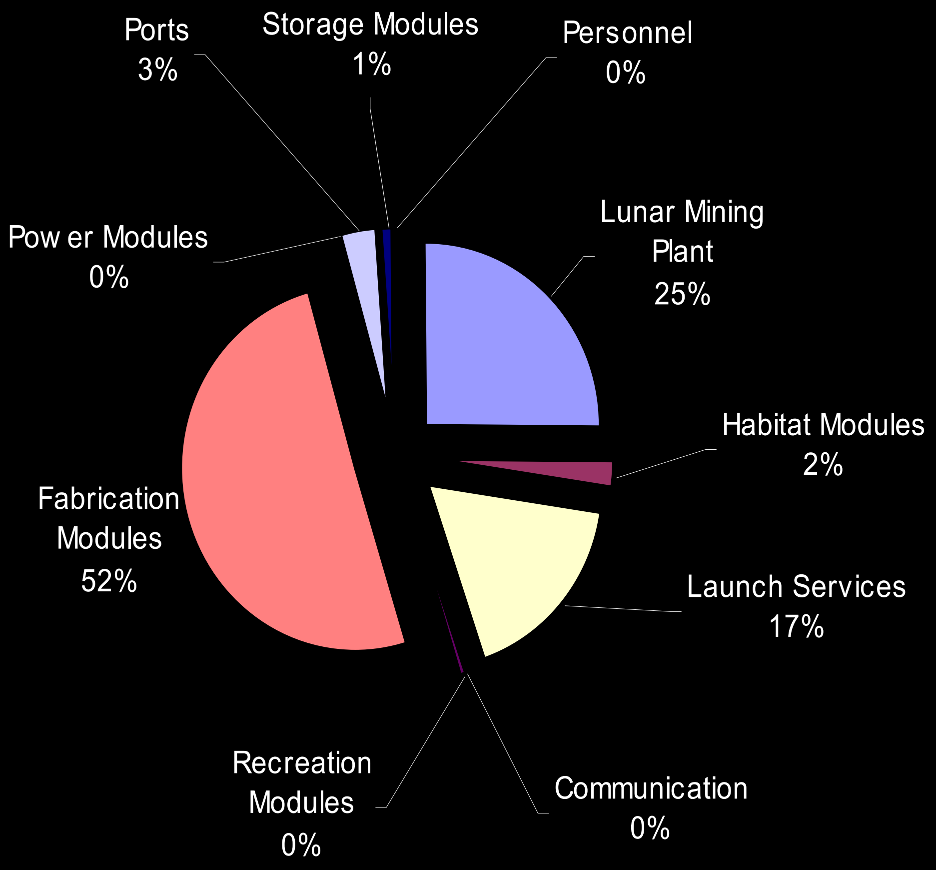
Cost Calculations – Phase (0)

- Calculate size based on necessary production output of fabrication modules
  - Driven by size of completed Heliopolis
  - Driven by necessary output of SPSs to break even within a time constraint which will attract investors
- Personnel rotation every 3 months
  - Health considerations – Zero-g environment in this phase
  - Increases mass to be sent up (i.e. Cost of Launch Services)

Cost Breakdown – Phase (0)

Element	Cost in M$Y2K	Cost Estimating Relationship
Launch Services	6,071.5	$2K / kg[1]
Habitat	767.7	# of Modules ^ (Learning Curve Power) * $ / ISS habitat module[2] * ratio of the required mass of our module to that of ISS habitat module * launch service scalar
Recreation	167.4	# of Modules ^ (Learning Curve Power) * $ / ISS habitat module[2] * ratio of the required mass of our module to that of ISS habitat module * launch service scalar
Fabrication	17,779.0	# of Modules ^ (Learning Curve Power) * $ / ISS habitat module[2] * ratio of the required mass of our module to that of ISS habitat module * launch service scalar
Power	18.8	Energy Required * (% Energy supplied by Solar Power * M$ / MW to build solar array[3] + % Energy supplied by Nuclear Power * M$ / MW to build nuclear generator[4] + % Energy supplied by Dynamic Power * M$ / MW to build dynamic generator[5]) * launch service scalar
Communications	2.6	(4516.7 + 1129.1 * Diameter (in m) + 691 * Life-time (yrs) + 359.9 * Range (AU))/1000 * launch service scalar (from LSMD CER)
Storage	406.5	# of Modules ^ (Learning Curve Power) * $ / ISS storage module[6] * ratio of the required mass of our module to that of ISS storage module * launch service scalar
Ports	1,082.3	# of Modules ^ (Learning Curve Power) * $ / ISS port[7] * ratio of the required mass of our port to mass of ISS port * launch service scalar
Personnel	5.0	Salaries + food + supplies
Lunar Mining Facility	8,884.2	Inflated cost from O'Neill's papers
Total	35,185.0	Sum of elements

Cost Breakdown – Phase (0)



- Total = $35,185.0M (Y2K)

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Cost – Phases (1 - 4)

- Phases (1 – 4): Construction of Heliopolis
  - Internalize all costs possible
    - Food, Manufacturing, Power, Milling, Refining, etc.
    - Only get from Earth what is absolutely necessary
      - Biomass, Soil, Water, Atmospheric Gases
  - Some unavoidable recurring costs
      - Salaries, Carbon for Refining, Propellant, Launch Services
  - Duration of each phase determined by % of Heliopolis Complete

Cost – Phase (1)

- Duration = 0.9 years
- Cost driven by Launch Services
  - Cost of component purchase minimal – raw materials
    - Biomass, Atmosphere, Simple Supplies
- Personnel cost is secondary driver
  - Assume # of personnel scales with % station complete
  - Earth still supplies all food requirements for Phase 1

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Cost Breakdown – Phase (1)

Element	Cost (M$Y2K)	Assumptions
Atmosphere	0.14	$0.001M / tonne of gas[1]
Attitude & Orbit	0.85	$1M / tonne of propellant[2], $0.2M / thruster[3]
Food Production	2.02	$128 / tonne biomass[4], $20 / tonne soil[5], $3 / tonne water[6]
Habitat	3.15	0.1 tonnes of supplies / person[7], $0.1M / tonne[8]
Launch Services	27,301.28	$1.588M / tonne to launch in during this phase[9]
Manufacturing	0.00	Internalized cost – material from moon, labor
Milling & Primary	0.00	Internalized cost – material from moon, labor
Power	0.00	Internalized cost – material from moon, labor
Radiation Shielding	0.00	Internalized cost – material from moon, labor
Recycling	0.00	Internalized cost – material from moon, labor
Refining	0.02	$425 / tonne of raw Carbon[10]
Structures	0.00	Internalized cost – material from moon, labor
Thermal	0.00	Internalized cost – material from moon, labor
Personnel	11.641	$7K / tonne of food[11], $0.1M for laborer[12], $0.16M for manager[13]
Total Cost of Phase (1)	$27,319.10M	See notes for references

Cost – Phase (2)

- Duration = 10.0 years
- Begin producing SPSs and earning revenue
- Costs continue to be driven by launch services
  - Much higher than Phase (1) due to duration
- Secondary Costs:
  - Propellant
    - To initiate spin-up
    - For Asteroid Retrieval Mission
    - For Solar Power Satellites
  - Biomass
  - Personnel

Cost – Phase (2)

- Personnel increases as % of station complete, but
  - now assume station economy only loses 22% of their salary
    - Personnel pays station for own food, lodging, etc.
    - 22% based on:
      - Avg. profit margin of American company[1]
      - Avg. % of salary savings of American household[2]
      - Guestimate on % external company's cost not paid to station[3]
  - station now houses non-working personnel

Cost Breakdown – Phase (2)

Element	Cost (M$Y2K)	Assumptions
Atmosphere	1.40	$0.001M / tonne of gas
Attitude & Orbit	24.53	$1M / tonne of propellant, $0.2M / thruster
Food Production	20.07	$128 / tonne biomass, $20 / tonne soil, $3 / tonne water
Habitat	5.41	0.1 tonnes of supplies / person, $0.1M / tonne
Launch Services	150,836.32	$0.8903M / tonne to launch in during this phase
Manufacturing	1.63	$1M / tonne of propellant (for SPSs)
Milling & Primary	0.00	Internalized cost – material from moon, labor
Power	0.00	Internalized cost – material from moon, labor
Radiation Shielding	0.00	Internalized cost – material from moon, labor
Recycling	0.00	Internalized cost – material from moon, labor
Refining	1.99	$425 / tonne of raw Carbon
Structures	0.00	Internalized cost – material from moon, labor
Thermal	0.00	Internalized cost – material from moon, labor
Personnel	6.55	$7K / tonne of food, $0.1M for laborer, $0.16M for manager
Total Cost of Phase (1)	**$150,897.89 M**	See notes on slide 59 for all references

Cost – Phase (3)

- Duration = 6.7 years
- Asteroid has been retrieved
  - No more Carbon needed from Earth
  - Precious Metal Revenue possible
- Cost still driven by Launch Services

Cost Breakdown – Phase (3)

Element	Cost (M$Y2K)	Assumptions
Atmosphere	1.27	$0.001M / tonne of gas
Attitude & Orbit	89.62	$1M / tonne of propellant, $0.2M / thruster
Food Production	18.21	$128 / tonne biomass, $20 / tonne soil, $3 / tonne water
Habitat	17.26	0.1 tonnes of supplies / person, $0.1M / tonne
Launch Services	50,099.60	$0.3254M / tonne to launch in during this phase
Manufacturing	47.01	$1M / tonne of propellant (for SPSs)
Milling & Primary	0.00	Internalized cost – material from moon, labor
Power	0.00	Internalized cost – material from moon, labor
Radiation Shielding	0.00	Internalized cost – material from moon, labor
Recycling	0.00	Internalized cost – material from moon, labor
Refining	0.00	Internalized cost – material from moon & asteroid, labor
Structures	0.00	Internalized cost – material from moon, labor
Thermal	0.00	Internalized cost – material from moon, labor
Personnel	26.60	$0.1M for laborer, $0.16M for manager
Total Cost of Phase (1)	$50,299.57M	See notes on slide 59 for references

Chad

Cost – Phase (4)

- Steady-state
- Cost Drivers
  - Propellant
    - SPSs
    - Attitude & Orbit
  - Launch Services
    - Assume that by this time, cost is $200 / kg
    - Significantly less shipping
      - No additional Atmosphere, Biomass, etc. required
  - Personnel
  - Supplies
    - Still need small supplies from Earth (e.g. medical supplies)

Cost Breakdown – Phase (4)

Element	Cost (M$Y2K)	Assumptions
Atmosphere	0.00	$0.001M / tonne of gas
Attitude & Orbit	18.62	$1M / tonne of propellant, $0.2M / thruster
Food Production	0.00	$128 / tonne biomass, $20 / tonne soil, $3 / tonne water
Habitat	28.83	0.1 tonnes of supplies / person, $0.1M / tonne
Launch Services	67.83	$0.2M / tonne to launch in during this phase
Manufacturing	32.22	$1M / tonne of propellant (for SPSs)
Milling & Primary	0.00	Internalized cost – material from moon, labor
Power	0.00	Internalized cost – material from moon, labor
Radiation Shielding	0.00	Internalized cost – material from moon, labor
Recycling	0.00	Internalized cost – material from moon, labor
Refining	0.00	Internalized cost – material from moon & asteroid, labor
Structures	0.00	Internalized cost – material from moon, labor
Thermal	0.00	Internalized cost – material from moon, labor
Personnel	43.55	$0.1M for laborer, $0.16M for manager
Total Cost of Phase (1)	$190.95M	See notes on slide 59 for references

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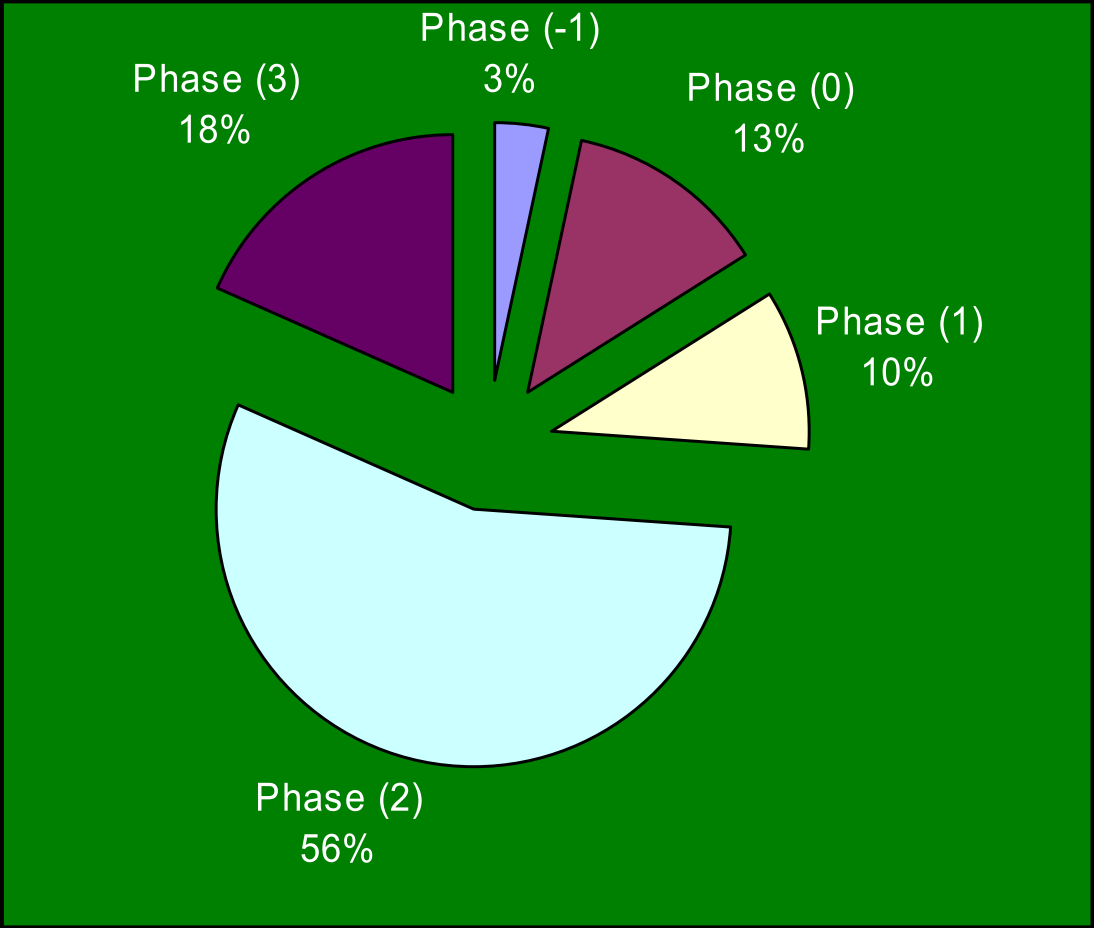
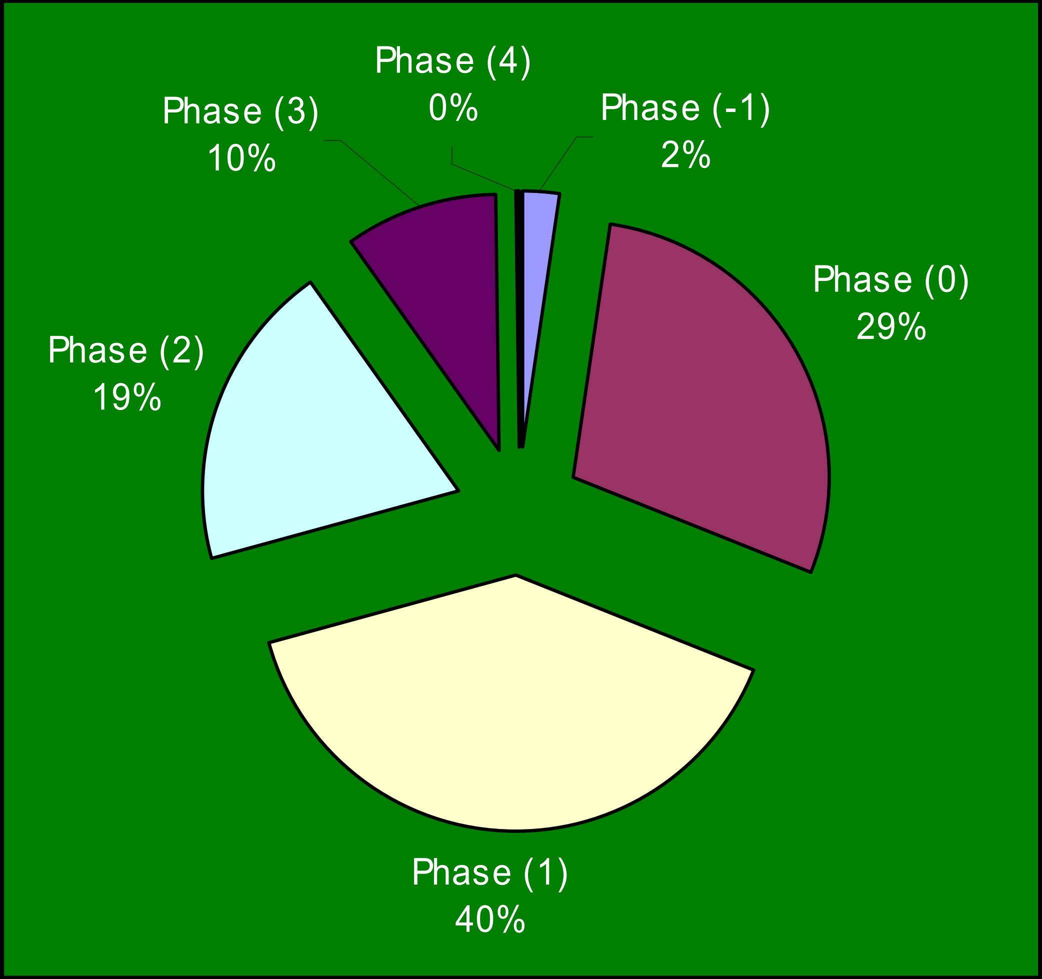
Cost Breakdown by Phase



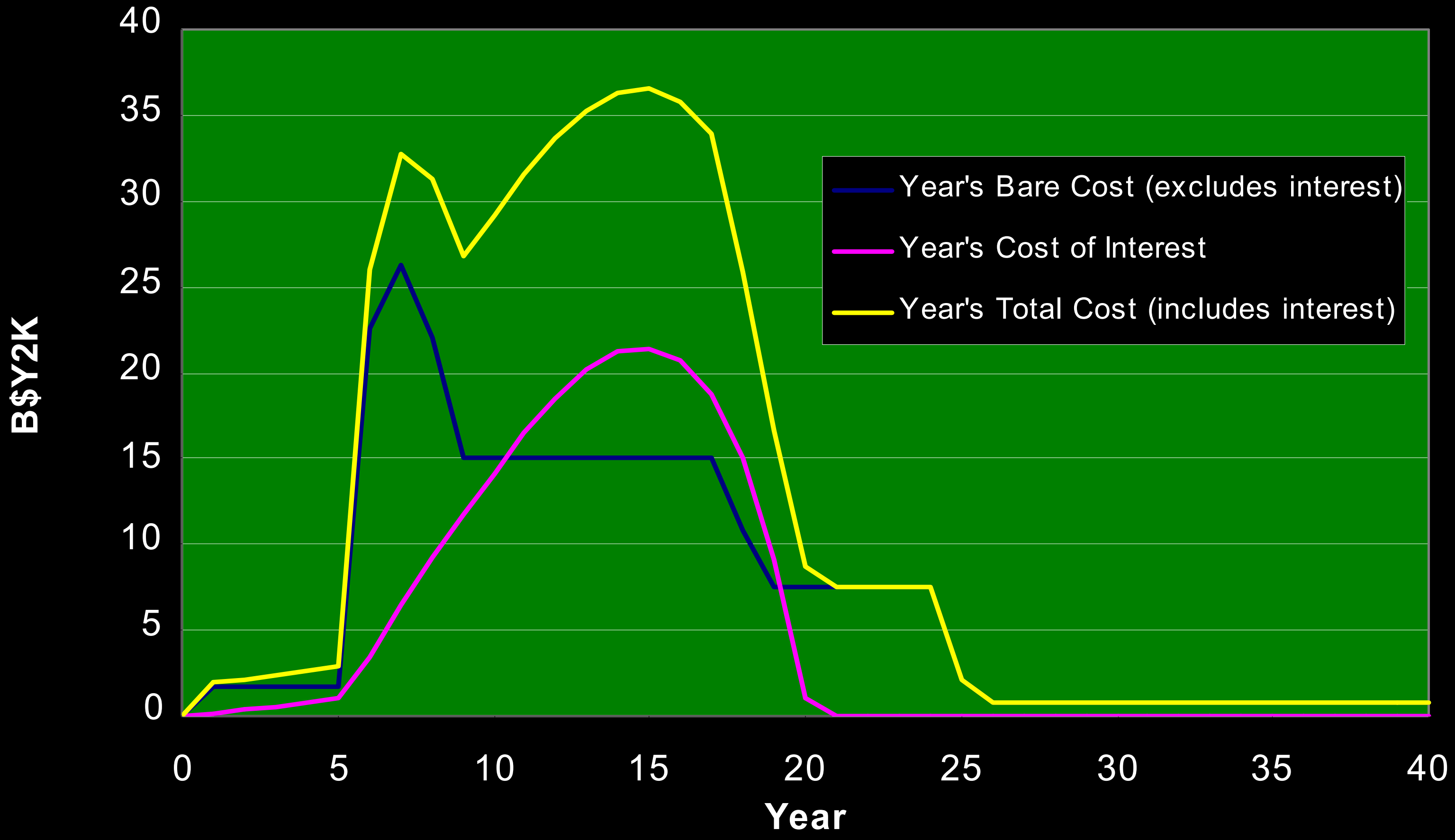
Phase	Cost in M$Y2K (excluding interest)
-1	8,830.6
0	35,185.0
1	27,319.1
2	150,897.9
3	50,299.6
Total	$272,532.2 (Y2K)

Cost / Year by Phase



Phase	Cost / Year (in M$Y2K)
-1	1,766.12
0	22,587.91
1	30,973.11
2	15,089.79
3	7,442.42
4	191.04

Cost by Year


40
35
30
25
20
15
10
5
0
B$Y2K
0
5
10
15
20
25
30
35
40
Year
Year's Bare Cost (excludes interest)
Year's Cost of Interest
Year's Total Cost (includes interest)

Revenue Generators

- Solar Power Satellites
  - Assume construct 1 per month
    - Size and output scale with % station complete
      - First satellite produced generates 225 MW
      - Phase (4), satellites produced generate 4500 MW
      - Linear fit between these points
    - Assume SPS lifetime exceeds 30 years
    - No SPS production until beginning of Phase (2)
  - Assume station will sell energy at $.05 / kW*hr (Y2K)
    - Low end of current competitive prices

Revenue Generators

- Suggested for inclusion in future studies
  - Tourism
    - Generates revenue through all phases
  - Communications Satellites
    - Opportunity Cost of time to build SPSs
  - Precious Metals
    - Generates revenue in phase (3) from asteroid refining
  - Zero-G Manufacturing
    - Opportunity Cost of time to build SPSs

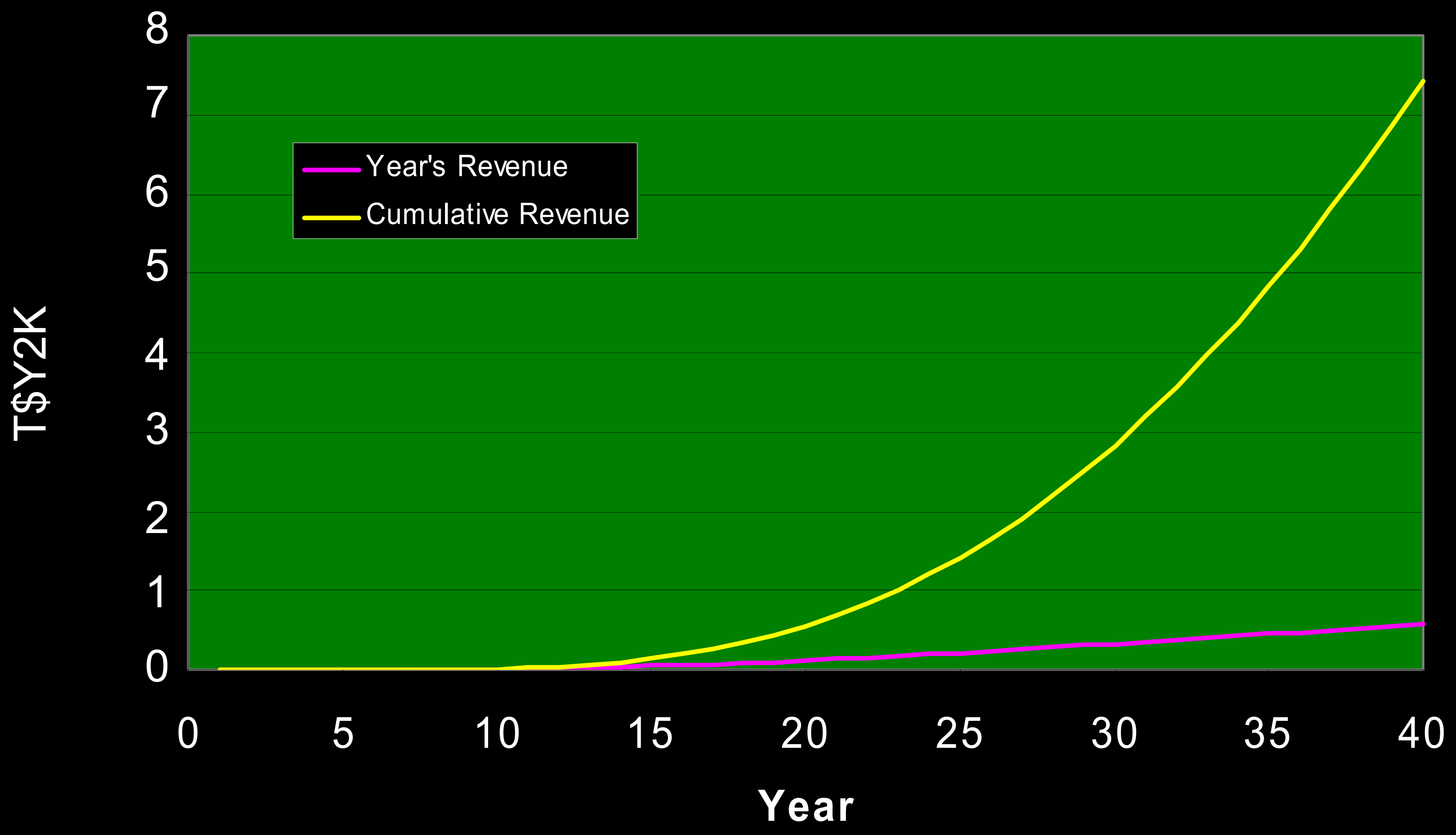
Time to Profit

- Accounting Profit in Year 15
- Economic Profit in Year 20
- Total Economic Profit at start of Phase 4 (Year 25)

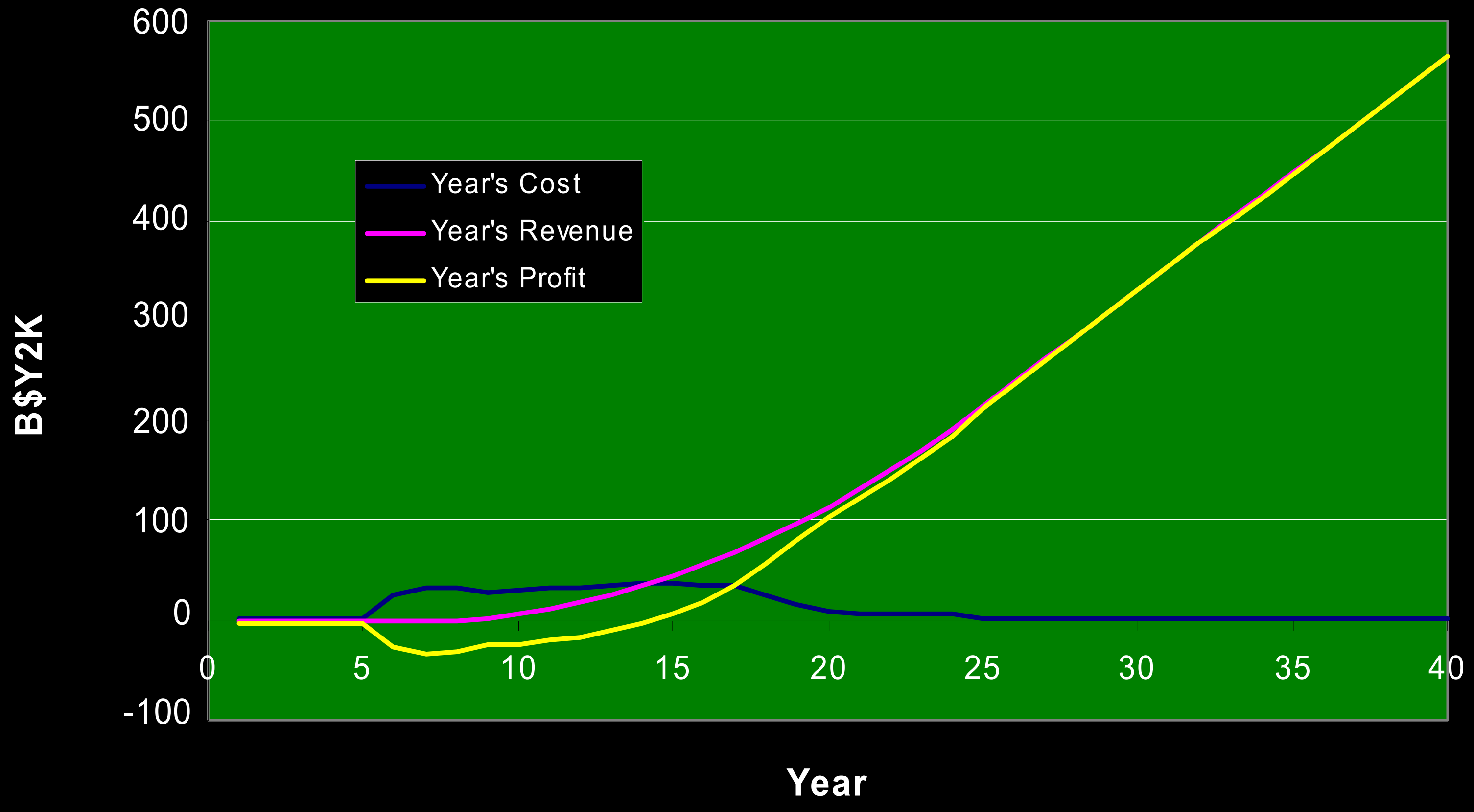
(Y2

$925,092,412,524

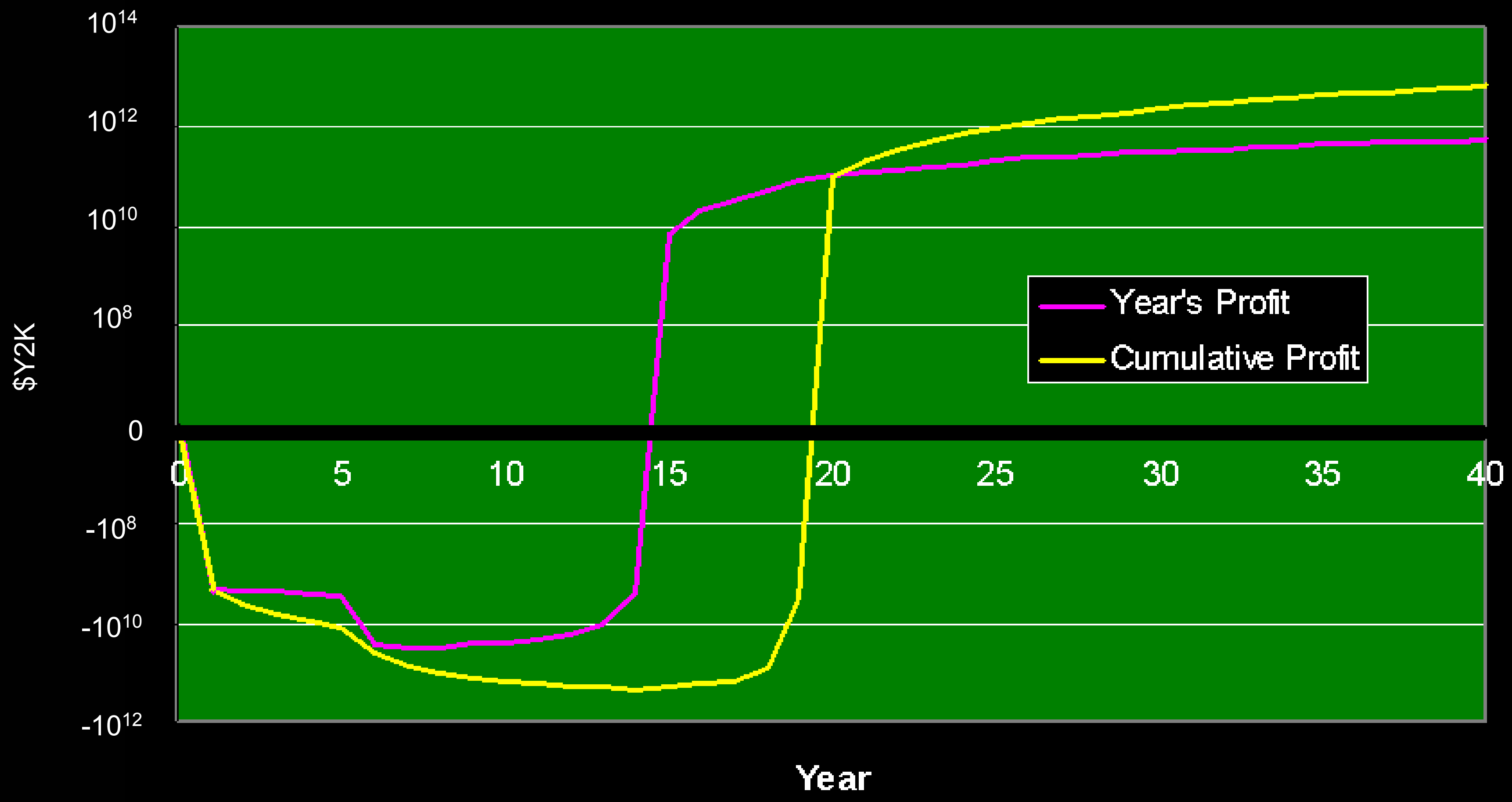
Total Revenue



Cash Flow Analysis by Year



Cash Flow Analysis (log scale)



Cumulative Cash Flow Analysis

Financial Conclusions

- Vital assumptions
  - Launch Services can handle project requirements for $2K / kg.
  - Construction and development costs scale with launch service
  - Cost of some systems can be "internalized" as opportunity cost (time)
  - Station can produce 1 SPS / month with output based on % of station complete
- Requires $105B initial investment over first 11 years
- Profitability
  - 15 years to accounting profitability
  - 20 years to economic profitability
  - $6.9T profit by year 40

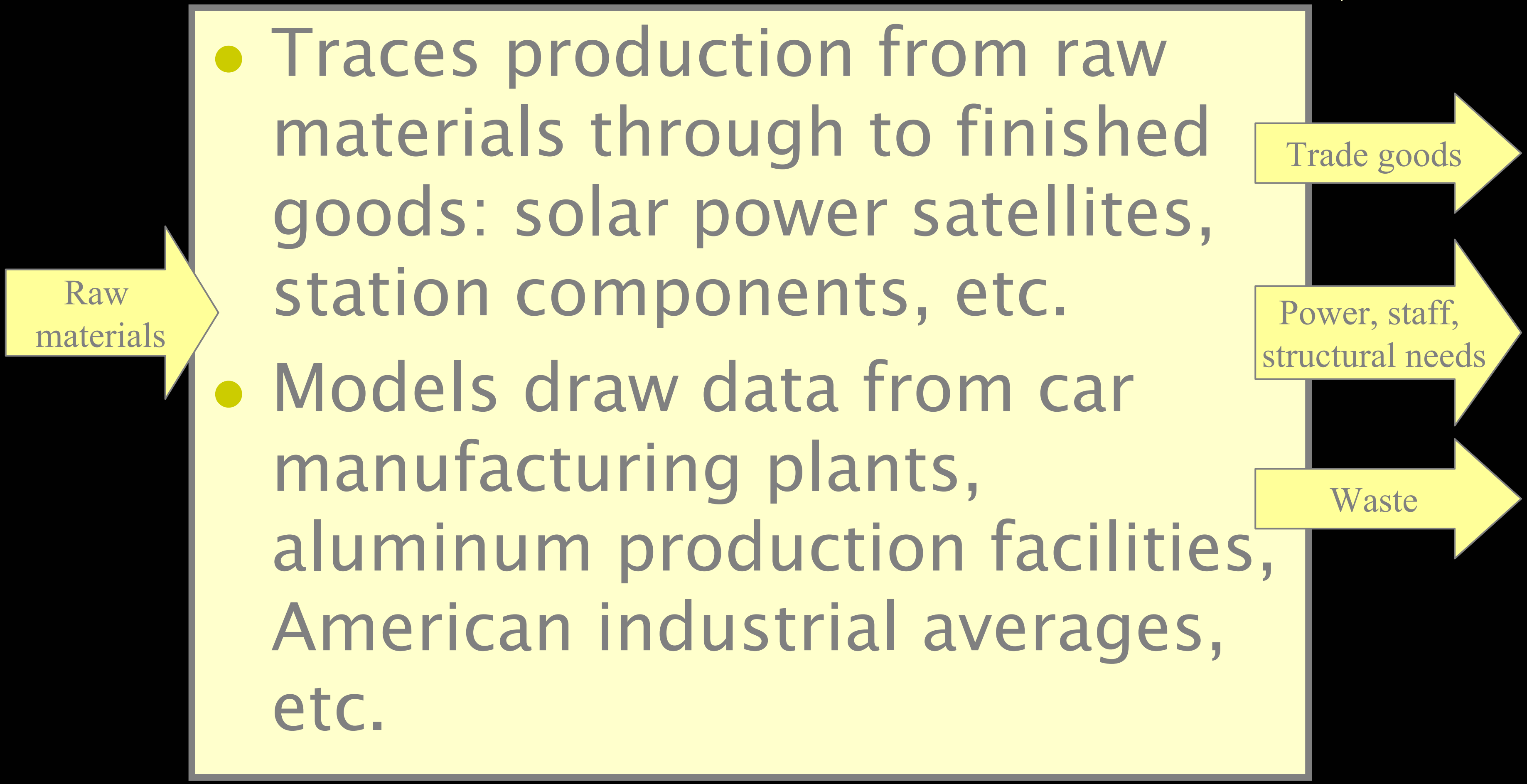
Technical Study: Overview

- Design Problems/Requirements & Solutions
- Shanty Town Description
- Heliopolis Description
- System-Level Summary
- Discussion of Economic Model
- **Explanation of Subsystem Models**
- Summary

Discussion of Subsystem Models

- Industrial Model
  - Manufacturing
  - Milling
  - Refining
- Habitat
- Food Production
- Atmosphere
- Recycling
- Personnel
- Power
- Thermal
- Structures
- Attitude Control
- Transportation
- Radiation Shielding

Industry Model Overview



Raw materials

- Traces production from raw materials through to finished goods: solar power satellites, station components, etc.
- Models draw data from car manufacturing plants, aluminum production facilities, American industrial averages, etc.

Trade goods

Power, staff, structural needs

Waste

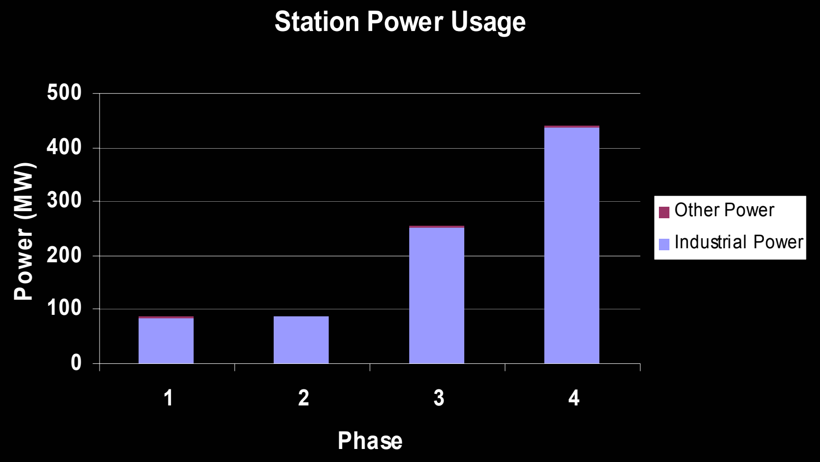
Industry Model Assumptions

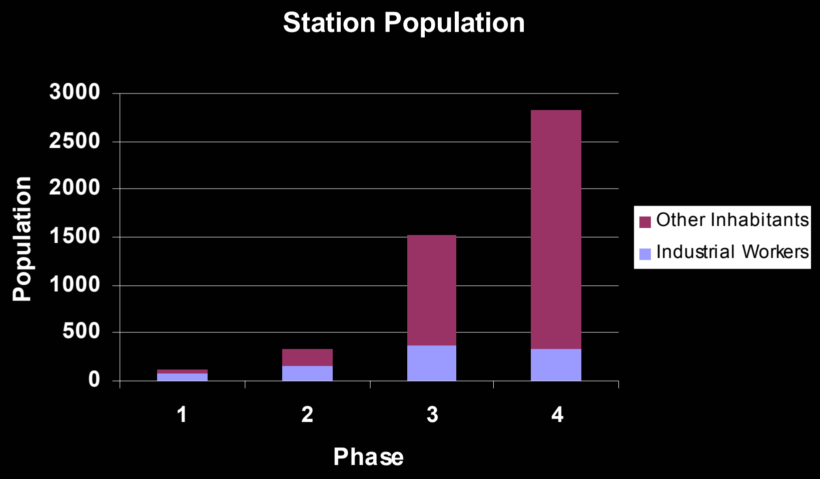
- Time-Independent Assumptions:
  - 20% waste heat
  - Average complexity is equivalent to car manufacturing
  - Logarithmic scaling of time-dependent variables

- Time-Dependent Assumptions:

Phase	Productivity Multiplier	Percent Non-Terrestrial Materials
1	2	0
2	2	10
3	5	33
4	10	99

Industry Model Results (1 of 2)

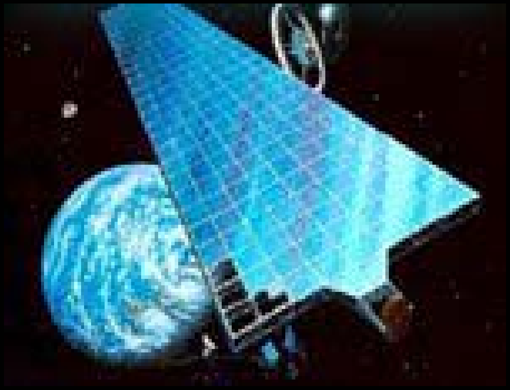


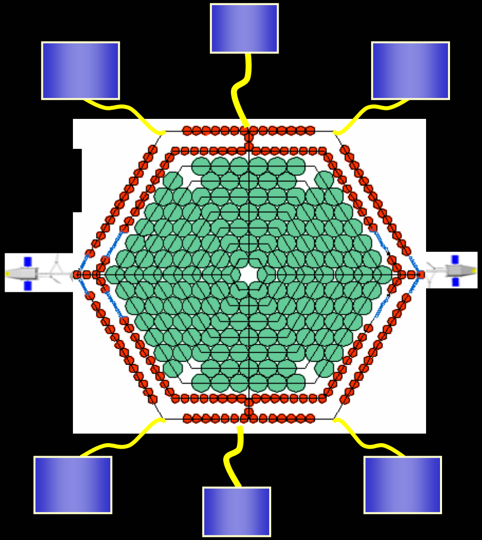


- Personnel employed peaks at 360 in phase 2, settles to ~340 in phase 4
- Requires 18,000 tonnes, 27,000 m^3 of facilities and machinery in phase 4
- Uses ~430 MW of power in phase 4

Industry Model Results (2 of 2)

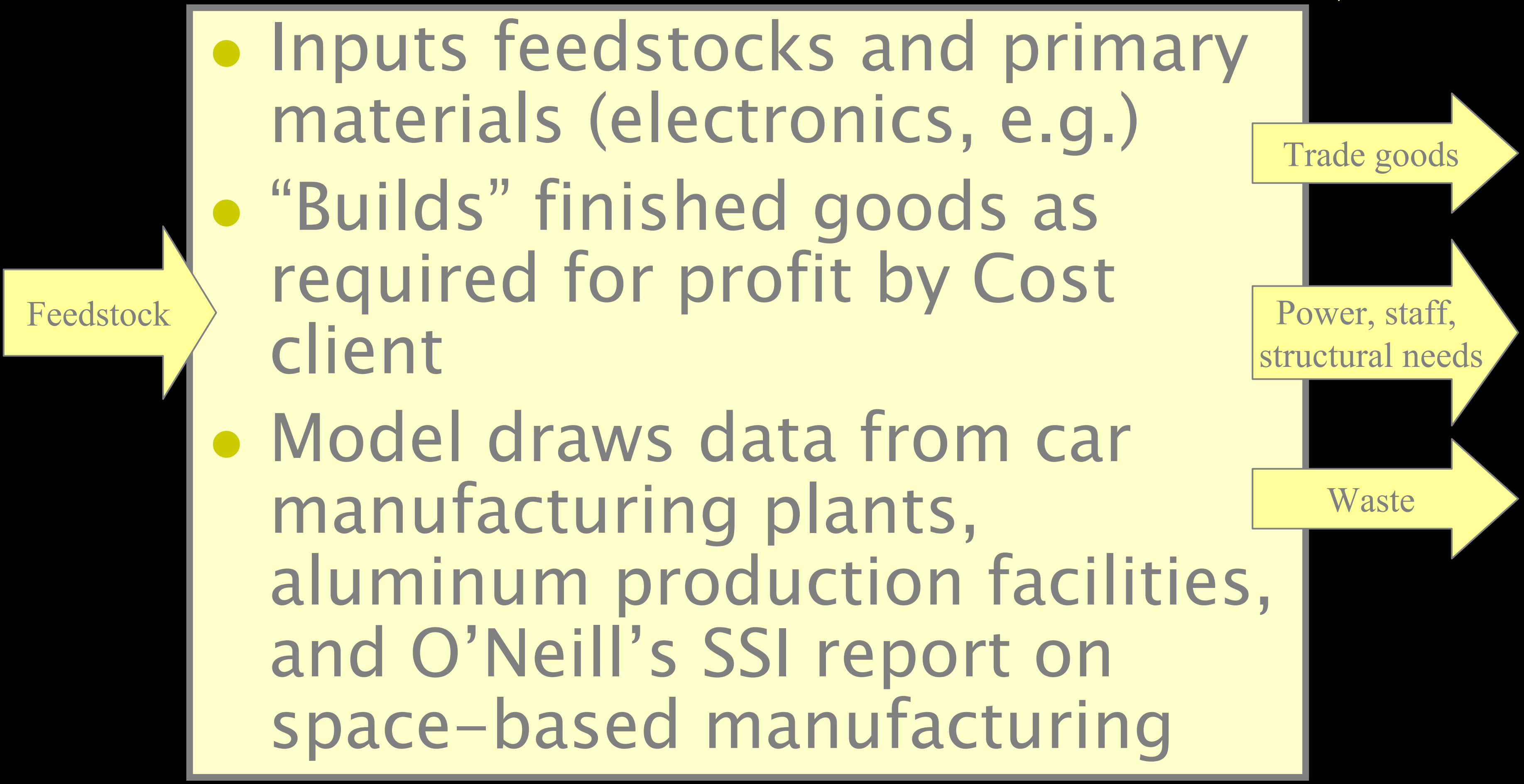
- Imports ~750 tonnes/month of material from Earth
- Exports 1 4.5 GW SPS and 2 Ansible[1]-class satellites/month by phase 4





[1] From 2000 LSMD study

Industry Model
Manufacturing Module



Feedstock

- Inputs feedstocks and primary materials (electronics, e.g.)
- “Builds” finished goods as required for profit by Cost client
- Model draws data from car manufacturing plants, aluminum production facilities, and O’Neill’s SSI report on space-based manufacturing

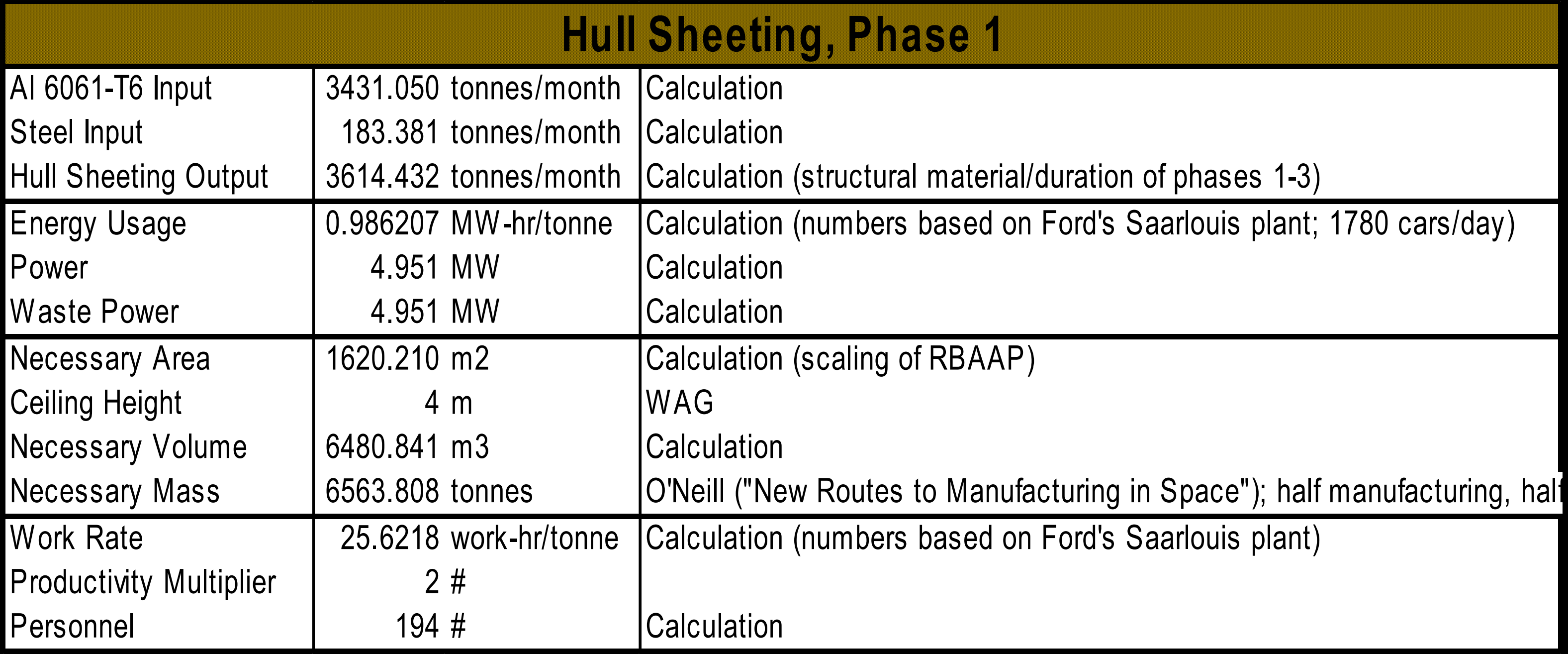
Trade goods

Power, staff, structural needs

Waste

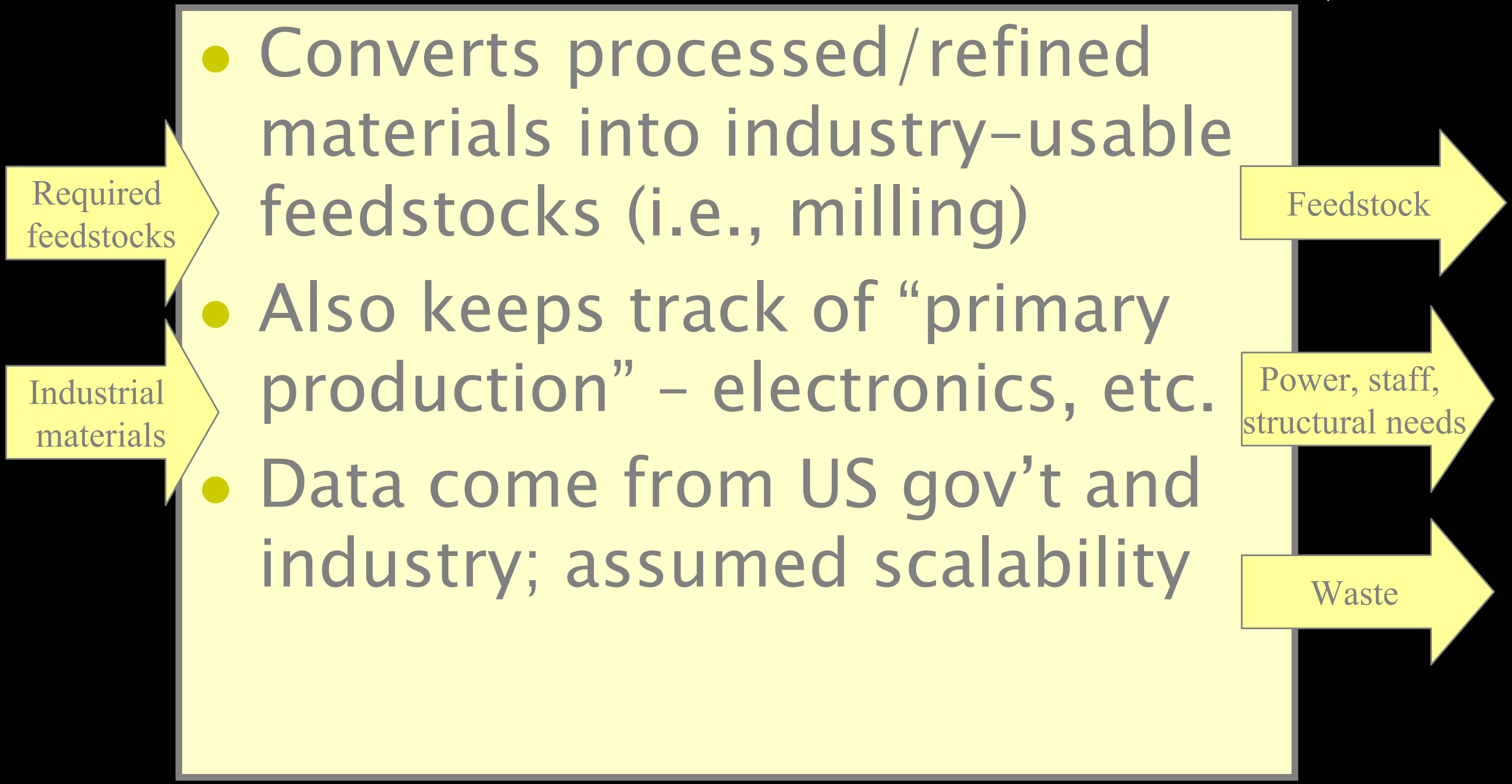
Industry Model Manufacturing: Process

- Sample calculation block: assembly of hull sheeting for construction of Heliopolis



Hull Sheeting, Phase 1			
Al 6061-T6 Input	3431.050	tonnes/month	Calculation
Steel Input	183.381	tonnes/month	Calculation
Hull Sheeting Output	3614.432	tonnes/month	Calculation (structural material/duration of phases 1-3)
Energy Usage	0.986207	MW-hr/tonne	Calculation (numbers based on Ford's Saarlouis plant; 1780 cars/day)
Power	4.951	MW	Calculation
Waste Power	4.951	MW	Calculation
Necessary Area	1620.210	m2	Calculation (scaling of RBAAP)
Ceiling Height	4	m	WAG
Necessary Volume	6480.841	m3	Calculation
Necessary Mass	6563.808	tonnes	O'Neill ("New Routes to Manufacturing in Space"); half manufacturing, half
Work Rate	25.6218	work-hr/tonne	Calculation (numbers based on Ford's Saarlouis plant)
Productivity Multiplier	2	#	
Personnel	194	#	Calculation

Industry Model
Milling Module



Required feedstocks

Industrial materials

- Converts processed/refined materials into industry-usable feedstocks (i.e., milling)
- Also keeps track of “primary production” – electronics, etc.
- Data come from US gov’t and industry; assumed scalability

Feedstock

Power, staff, structural needs

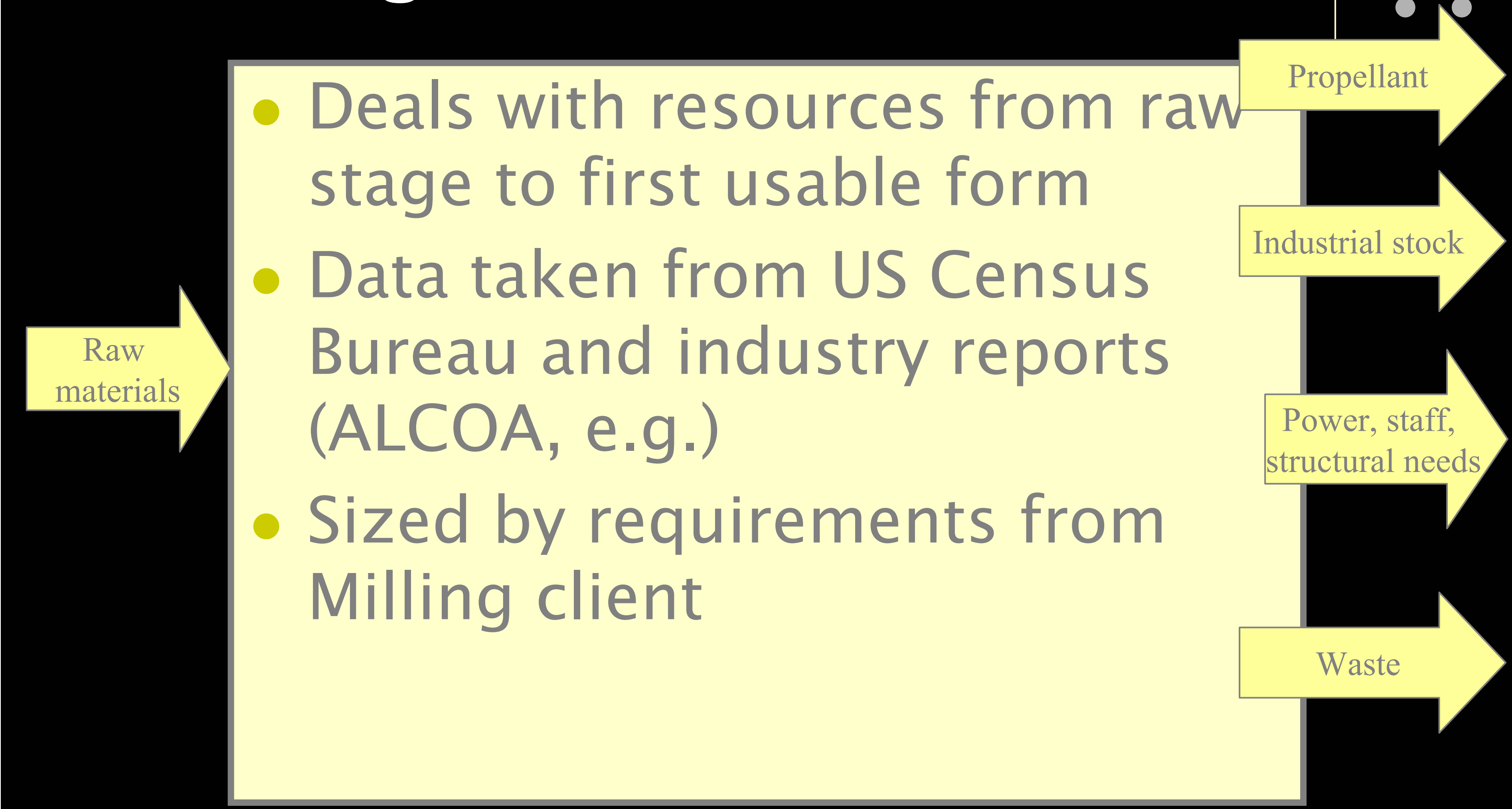
Waste

Industry Model Milling: Process

- Inputs required feedstocks from Manufacturing
- Calculates required material supplies
- Outputs available feedstocks

Aluminum Milling			
Raw Aluminum Input	20.952	tonnes/month	Calculation
Processing Efficiency	98	%	WAG
Aluminum Stock Output	20.533	tonnes/month	Calculation (per capita US productivity; USCB)
Scrap Output	0.419	tonnes/month	Calculation
Energy Usage	0.308	MW-hr/tonne	
Power Efficiency	80	%	WAG
Power	0.000	MW	Calculation
Waste Power	0.000	MW	Calculation
Necessary Area	8050.507	m2	Calculation (scaling of RBAAP, 5-1 better than 1940s, offset of 100 m2)
Ceiling Height	4	m	WAG
Necessary Volume	32202.027	m3	Calculation
Necessary Mass	805.051	tonnes	WAG (100 kg/m2)
Work Rate	12.496	work-hr/tonne	Calculation (ALCOA's Troutdale plant)
Automation	95	%	Mike's numbers from 1st term
Personnel	3	#	Calculation

Industry Model
Refining Module



Raw materials

- Deals with resources from raw stage to first usable form
- Data taken from US Census Bureau and industry reports (ALCOA, e.g.)
- Sized by requirements from Milling client

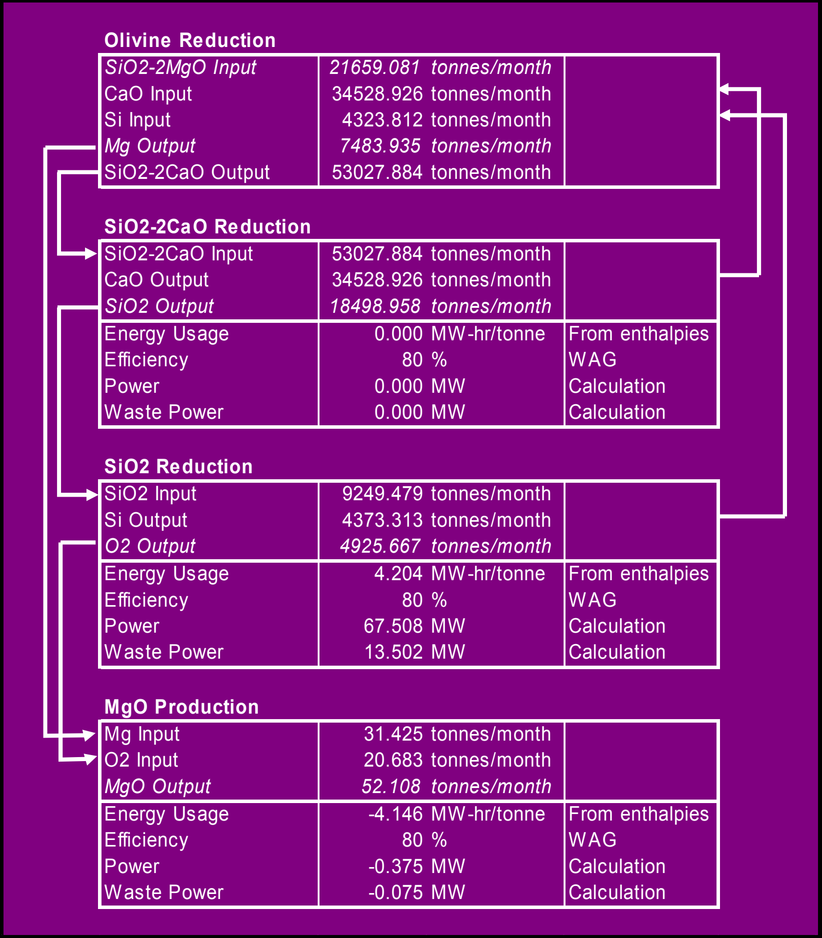
Propellant

Industrial stock

Power, staff, structural needs

Waste

Industry Model Refining: Process



Olivine Reduction

SiO2-2MgO Input	*21659.081 tonnes/month*	
CaO Input	34528.926 tonnes/month	
Si Input	4323.812 tonnes/month	
Mg Output	*7483.935 tonnes/month*	
SiO2-2CaO Output	53027.884 tonnes/month	

SiO2-2CaO Reduction

SiO2-2CaO Input	53027.884 tonnes/month	
CaO Output	34528.926 tonnes/month	
SiO2 Output	*18498.958 tonnes/month*	
Energy Usage	0.000 MW-hr/tonne	From enthalpies
Efficiency	80 %	WAG
Power	0.000 MW	Calculation
Waste Power	0.000 MW	Calculation

SiO2 Reduction

SiO2 Input	9249.479 tonnes/month	
Si Output	4373.313 tonnes/month	
O2 Output	*4925.667 tonnes/month*	
Energy Usage	4.204 MW-hr/tonne	From enthalpies
Efficiency	80 %	WAG
Power	67.508 MW	Calculation
Waste Power	13.502 MW	Calculation

MgO Production

Mg Input	31.425 tonnes/month	
O2 Input	20.683 tonnes/month	
MgO Output	*52.108 tonnes/month*	
Energy Usage	-4.146 MW-hr/tonne	From enthalpies
Efficiency	80 %	WAG
Power	-0.375 MW	Calculation
Waste Power	-0.075 MW	Calculation

- Sample calculation block: reduction of lunar olivine
- Checks for closed loops – flags net inputs or outputs (italics)

Habitat Model

Population

Space requirements

- Characterizes the living spaces of Heliopolis
- Space per person (pps) increases ~33% with each phase to reflect the increasin standard of living within the colony
- Some components, such as public space, shops & services, are not present in ini shanty phase
- Phase 3 colony has spaces comparable to Stanford Torus study in 1976
- Completed colony has projected area pe person comparable to New York City

Area

Volume

Mass

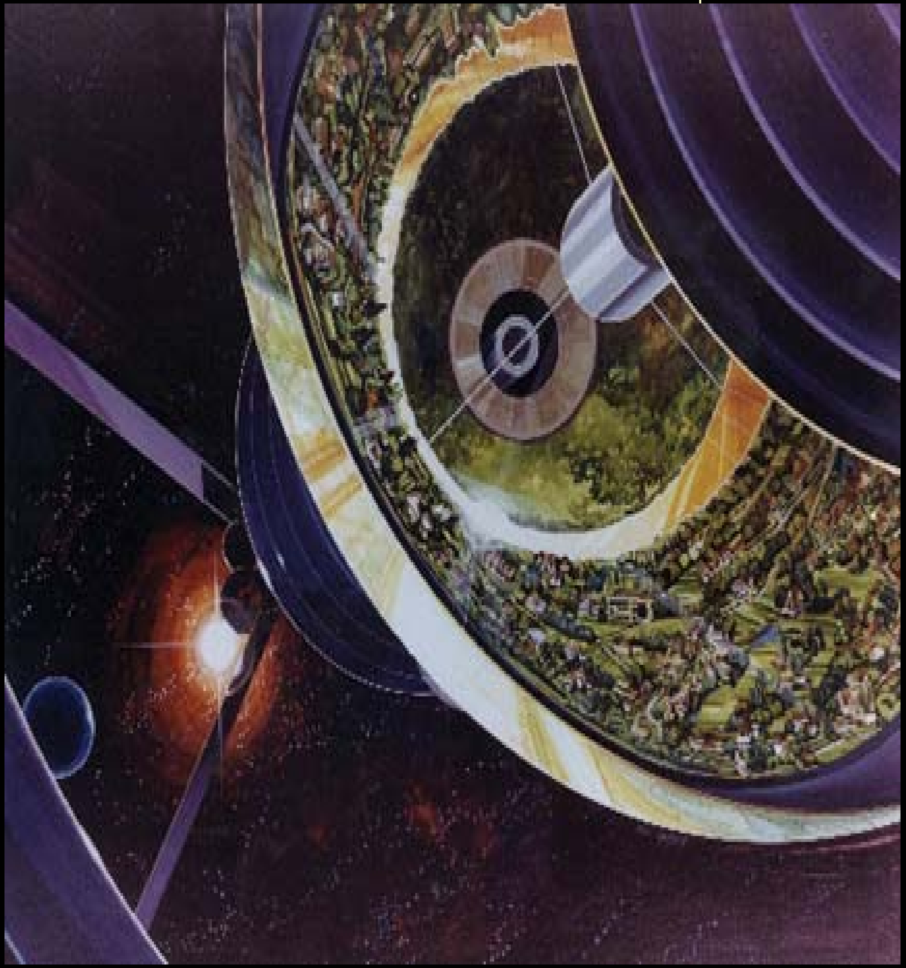
Habitat Model Spaces

Spaces Considered

- **Living Quarters** – bed, bath, kitchen, den, dining rooms
- **Entertainment** – cinema, theatre, video games, internet
- **Public space** – parks, open fields, gardens
- **Recreation** – exercise equipment, track, swim pool
- **Shops** – general & grocery store
- **Service Industry** – personal goods
- **Offices** – government, trade, accounting
- **Hospital** – telemedicine robotic facility
- **School** – library, teleducation facility
- **Cafeteria** – food services away from home
- **Walk ways** – escalators, moving floors, light rail

Habitat Model Notes

- Space requirements per person for each phase are presented in next 4 tables
- Characterization of Habitat for each phase presented in final chart
- Numbers give idea how habitat is expected to grow in size and comfort



Habitat Phase 1 Assumptions

Habitat Space per Person	mass	volume	area	height	power normal	power emergency	metal waste	plastic waste
Section	kg/m2	m3/pps	m2/pps	m	kW/pps	kW/pps	kg/monthpps	kg/monthpps
Living Quarters	1	10	5	2	0.05	0.005	0.5	1.0
Entertainment	1	3	1	3	0.1	0.001	0.0	0.0
Public Space	0	0	0	0	0.02	0	0.0	0.0
Cafeteria	1	7.5	3	2.5	0.1	0.003	0.0	0.2
Recreation	3	9	3	3	0.1	0.003	0.0	0.0
Shops	0	0	0	0	0.05	0	0.0	0.1
Service Industry	0	0	0	0	0.05	0	0.0	0.0
Offices	1	5	2	2.5	0.05	0.002	0.0	0.0
Hospital	1	1.25	0.5	2.5	0.1	0.1	0.1	0.1
School	1	2.5	1	2.5	0.03	0.001	0.0	0.0
Walkways	1	9	3	3	0.02	0.003	0.0	0.0
Totals	1.32	47.25	18.5	2.55	0.67	0.118	0.6	1.4

*Values for space requirements scaled down ~80% from 1975 Stanford Study

Habitat Phase 2 Assumptions

Habitat Space per Person	mass	volume	area	height	power normal	power emergency	metal waste	plastic waste
Section	kg/m2	m3/pps	m2/pps	m	kW/pps	kW/pps	kg/monthpps	kg/monthpps
Living Quarters	8	100	40	2.5	0.1	0.04	1.5	0.8
Entertainment	8	5	1	5	0.15	0.001	0.0	0.0
Public Space	4	300	10	30	0.02	0.01	0.0	0.0
Cafeteria	6	2.5	1	2.5	0.1	0.001	0.0	0.3
Recreation	12	6	2	3	0.1	0.002	0.0	0.0
Shops	20	2.5	1	2.5	0.05	0.001	0.0	0.2
Service Industry	8	2.5	1	2.5	0.05	0.001	0.0	0.0
Offices	8	2.5	1	2.5	0.05	0.001	0.0	0.0
Hospital	6	2.5	1	2.5	0.1	0. 1	0.2	0.2
School	6	5	2	2.5	0.05	0.002	0.0	0.0
Walkways	2	18	6	3	0.02	0.006	0.0	0.0
Totals	7.03	446.5	66	6.77	0.79	0.165	1.65	1.35

*Values for space requirements scaled down ~25% from 1975 Stanford Study

Habitat Phase 3 Assumptions

Habitat Space per Person	mass	volume	area	height	power normal	power emergency	metal waste	plastic waste
Section	kg/m2	m3/pps	m2/pps	m	kW/pps	kW/pps	kg/monthpps	kg/monthpps
Living Quarters	8	122.5	49	2.5	0.15	0.049	1.9	0.9
Entertainment	8	10	2	5	0.15	0.002	0.0	0.0
Public Space	4	450	15	30	0.02	0.015	0.0	0.0
Cafeteria	6	2.5	1	2.5	0.1	0.001	0.0	0.4
Recreation	12	6	2	3	0.15	0.002	0.0	0.0
Shops	20	5	2	2.5	0.1	0.002	0.0	0.2
Service Industry	8	5	2	2.5	0.1	0.002	0.0	0.0
Offices	8	2.5	1	2.5	0.05	0.001	0.0	0.0
Hospital	6	5	2	2.5	0.1	0.1	0.2	0.2
School	6	7.5	3	2.5	0.07	0.003	0.0	0.0
Walkways	2	24	8	3	0.02	0.008	0.0	0.0
Totals	6.99	640	87	7.36	1.01	0.185	2.0625	1.6875

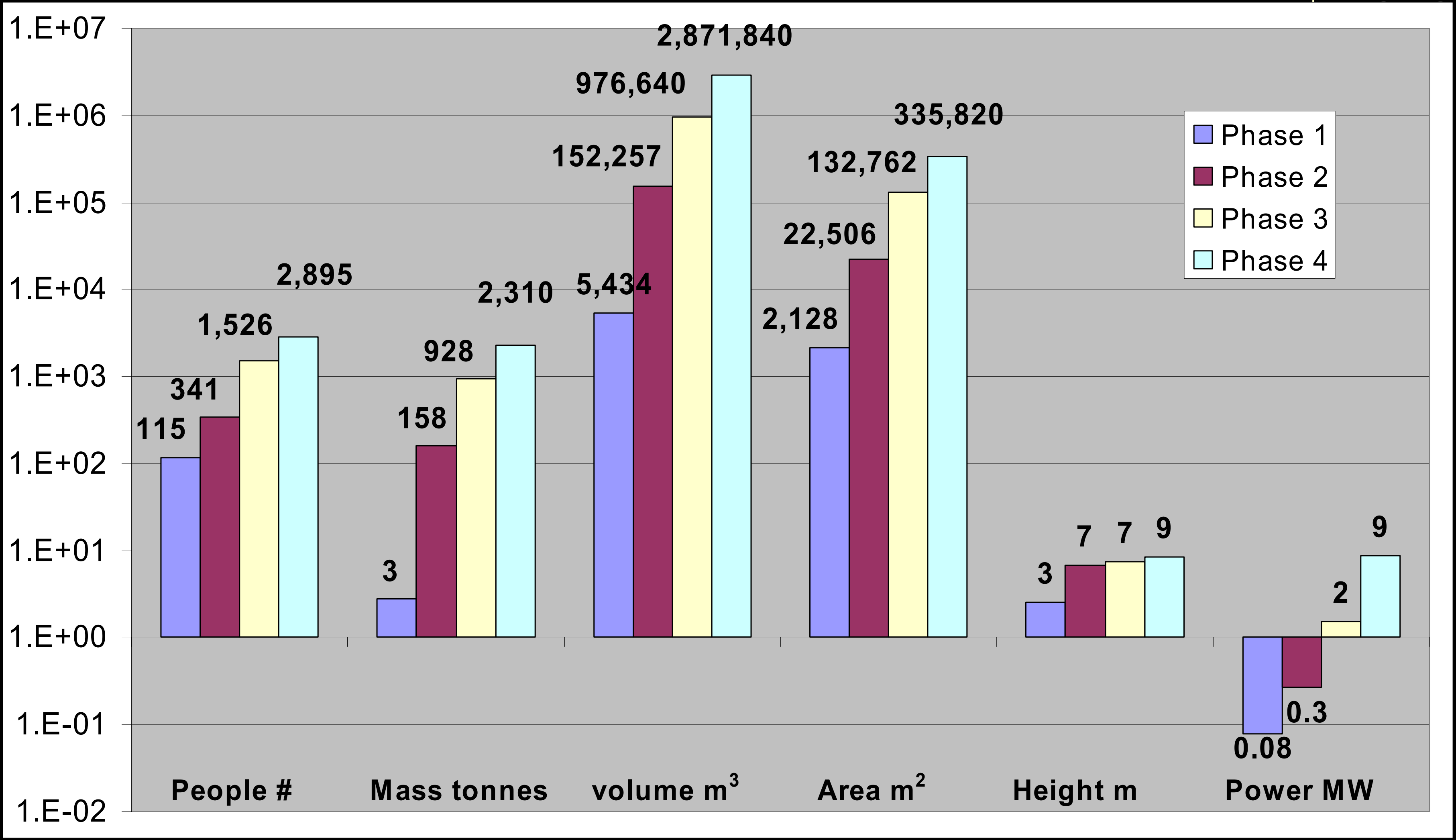
*Values for space requirements from 1975 Stanford Study

Habitat Phase 4 Assumptions

Habitat Space per Person	mass	volume	area	height	power normal	power emergency	metal waste	plastic waste
Section	kg/m2	m3/pps	m2/pps	m	kW/pps	kW/pps	kg/monthpps	kg/monthpps
Living Quarters	8	150	60	2.5	2	0.06	2.3	1.2
Entertainment	8	10	2	5	0.2	0.002	0.0	0.0
Public Space	4	750	25	30	0.02	0.025	0.0	0.0
Cafeteria	6	5	2	2.5	0.1	0.002	0.0	0.5
Recreation	12	9	3	3	0.2	0.003	0.0	0.0
Shops	20	7.5	3	2.5	0.1	0.003	0.0	0.2
Service Industry	8	5	2	2.5	0.1	0.002	0.0	0.0
Offices	8	5	2	2.5	0.1	0.002	0.0	0.0
Hospital	6	10.5	3	3.5	0.1	0.1	0.2	0.2
School	6	10	4	2.5	0.1	0.004	0.0	0.0
Walkways	2	30	10	3	0.02	0.01	0.0	0.0
Totals	6.88	992	116	8.55	3.04	0.213	2.578125	2.109375

*Values for space requirements scaled up ~33% from 1975 Stanford Study

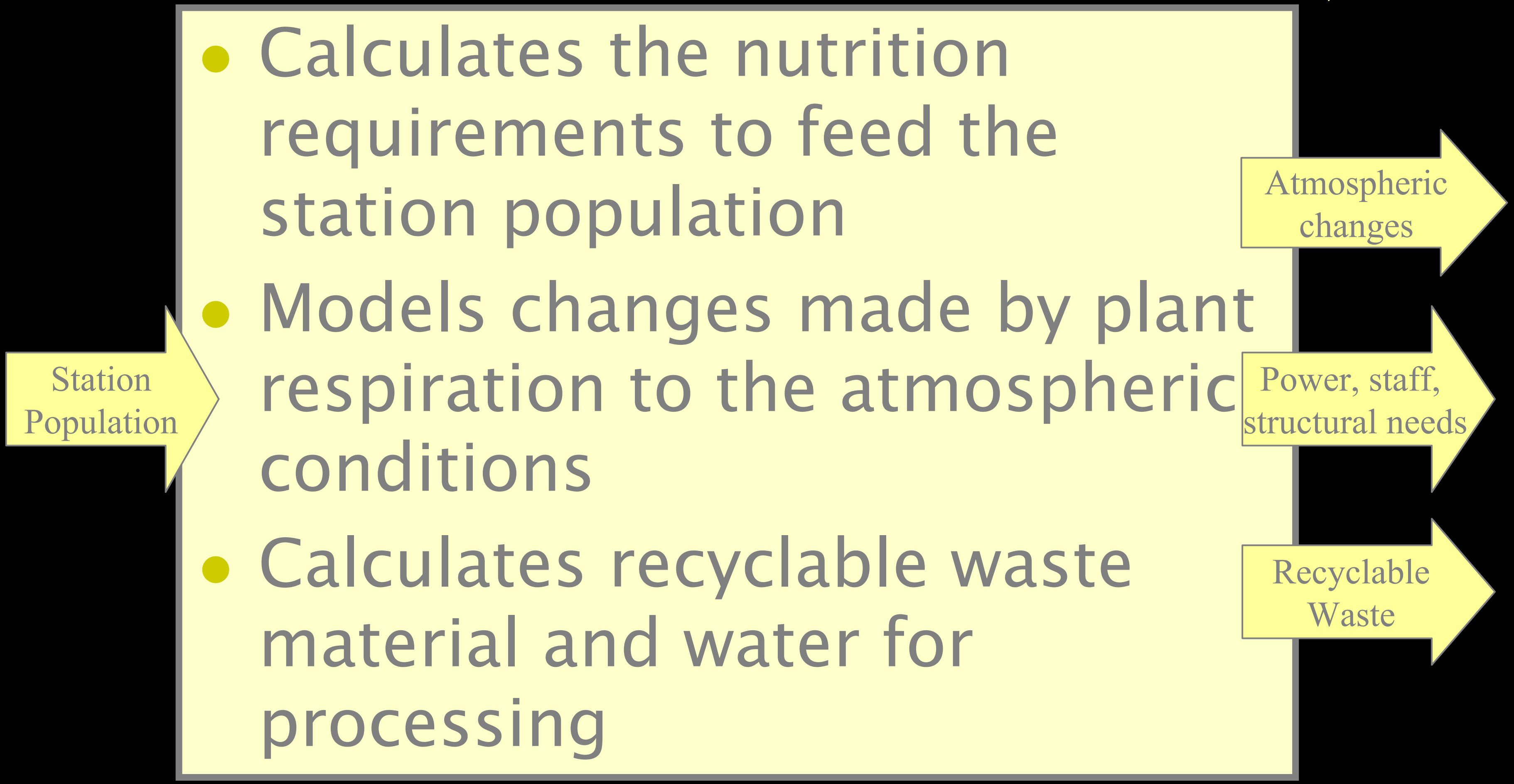
Habitat Model Results Summary



Life Support Models

- System models for supporting humans in space
- Includes:
  - Food Production
  - Atmosphere
  - Recycling

Food Production Model: Overview



Station Population

- Calculates the nutrition requirements to feed the station population
- Models changes made by plant respiration to the atmospheric conditions
- Calculates recyclable waste material and water for processing

Atmospheric changes

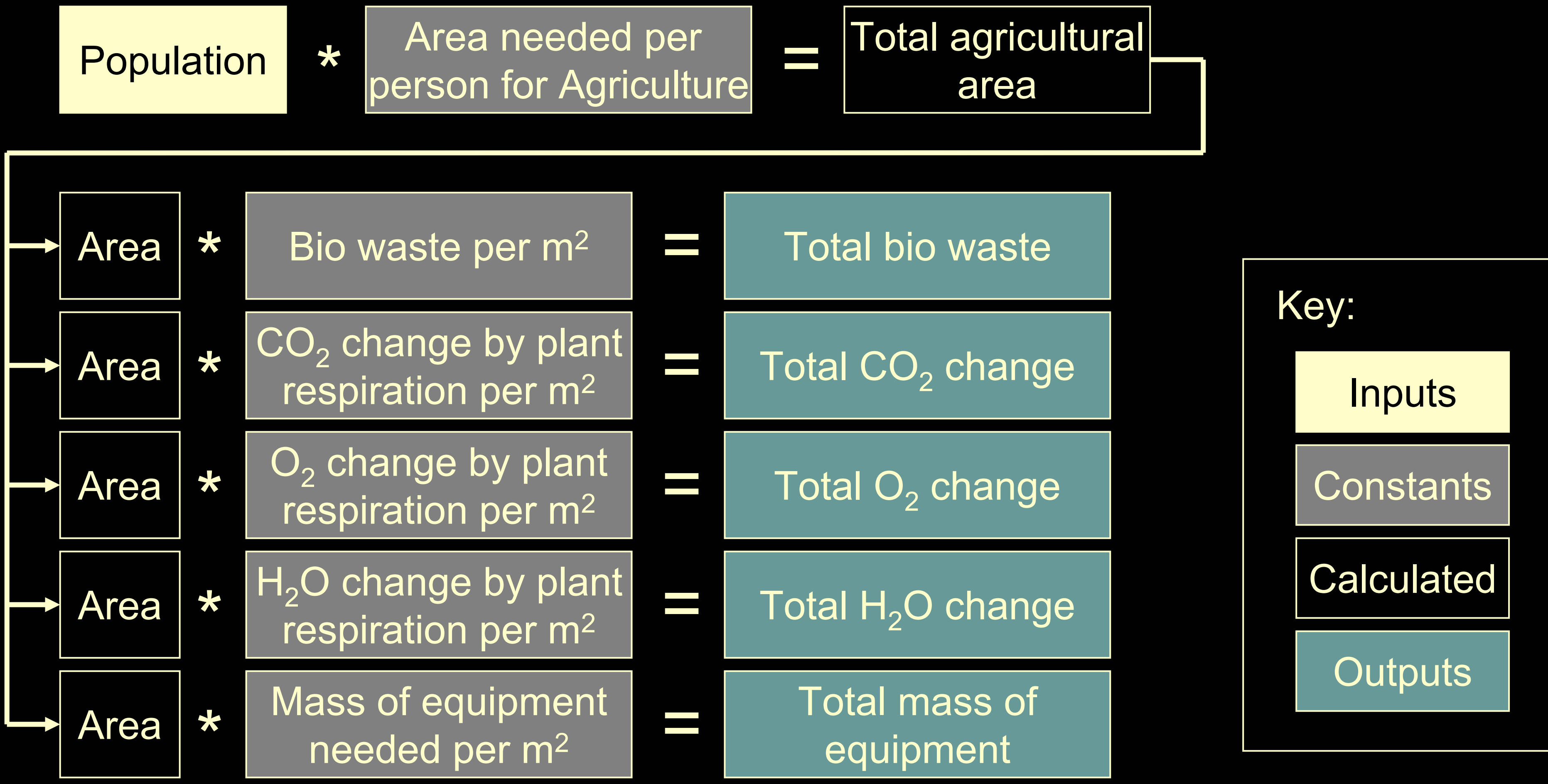
Power, staff, structural needs

Recyclable Waste

Food Production Model: Assumptions

- Farming technologically stable
  - Crop yields will increase (i.e. bioengineered plants) but not by more than 2x.
  - Equipment will not undergo major technological changes over the current timetable
  - Standard soil farming proven technology and less labor intensive than hydroponics or airponics

Food Production Model: Calculations



Population * Area needed per person for Agriculture = Total agricultural area

Area * Bio waste per m² = Total bio waste

Area * CO_2 change by plant respiration per m² = Total CO_2 change

Area * O_2 change by plant respiration per m² = Total O_2 change

Area * H_2O change by plant respiration per m² = Total H_2O change

Area * Mass of equipment needed per m² = Total mass of equipment

Key:
- Inputs
- Constants
- Calculated
- Outputs

Food Production Model: Description

- Conditions
  - Normal Earth gravity for crops
  - Reflected light from station mirrors – no need for artificial light
  - Climate control optimizes atmospheric conditions for crops
  - Provides “visible green spaces” for people on the station

Food Production Model: Results

- Phase 1
  - No onboard food production
  - Regular re-supply needed
  - Small impact to station mass and volume

Staff, Food Production	0	#
Waste power, Food Production	0.01	MW
O2 change by Food Production	0	kg/day
CO2 change by Food Production	0	kg/day
H20 vapor change by Food Production	0	kg/day
Water waste from Food Production	0	kg/day
Food Re supply required from Earth	2.5	tonnes/month
Water Re supply required from Earth (recycled)	0	tonnes/month
Requested Sunlight, natural	0	W/m2
Mass of soil	0	tonnes
Mass of water	0	tonnes
Mass of biomass	0	tonnes

All values calculated in the model

Food Production Model: Results

- Phase 4
  - Onboard food production meets station needs
  - No regular re-supply
  - Adds significant mass and area requirements on the overall structure
  - Staff accounts for about 10% of total population

Staff, Food Production	361	#
Waste power, Food Production	0.3	MW
O2 change by Food Production	5766	kg/day
CO2 change by Food Production	− 8649	kg/day
H20 vapor change by Food Production	432450	kg/day
Water waste from Food Production	432	kg/day
Food Re supply required from Earth	0	tonnes/month
Water Re supply required from Earth (recycled)	0	tonnes/month
Requested Sunlight, natural	400	W/m2
Mass of soil	21622	tonnes
Mass of water	1297 31136	tonnes
Mass of biomass	4	tonnes

All values calculated in the model

Atmosphere Model: Overview

- Book keeps the changes made to the atmosphere
- Sums changes made by other subsystem models
- Calculates changes needed from Recycling model to maintain desired atmospheric conditions
- Outputs air circulation equipment requirements

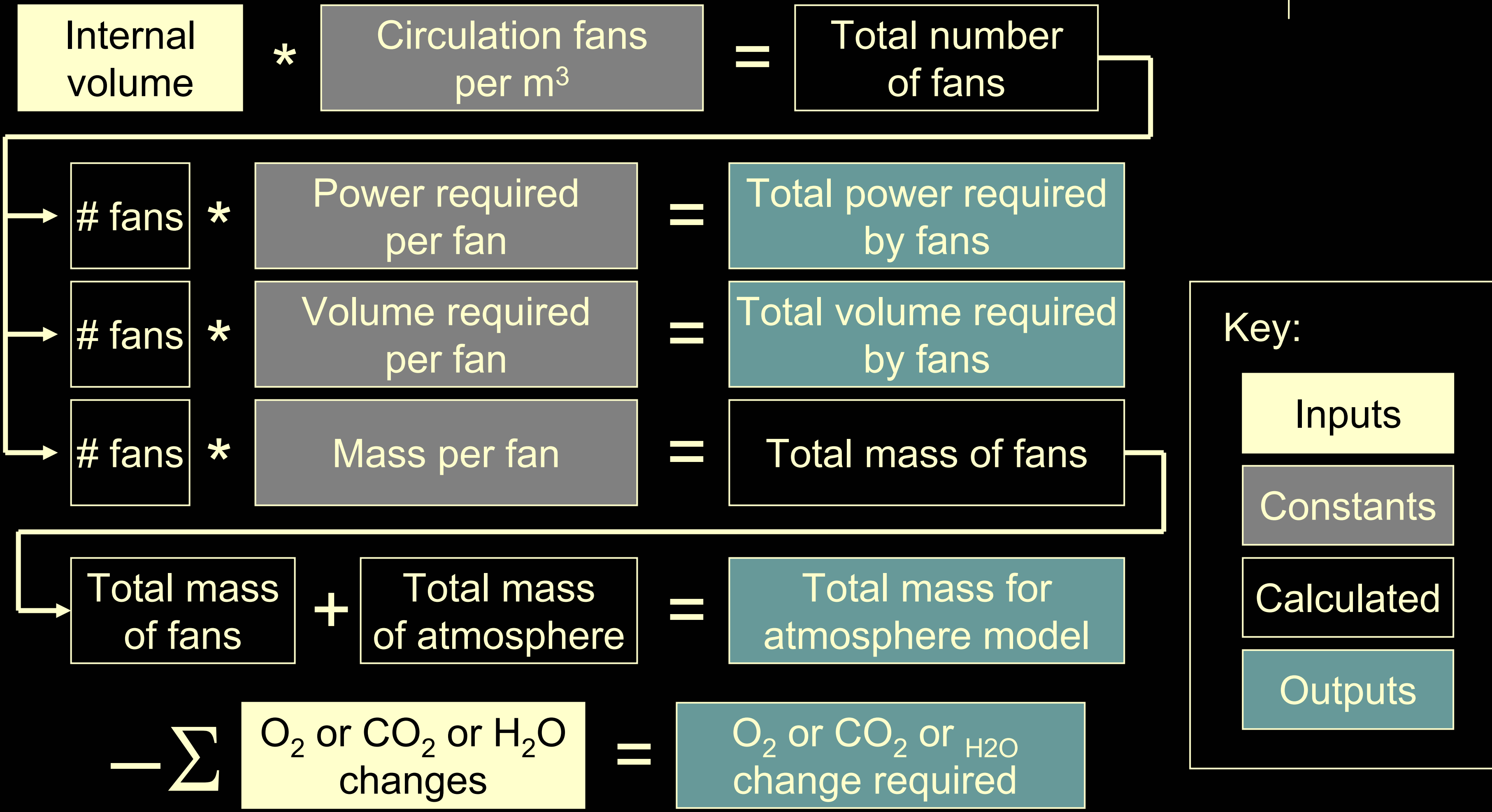
Atmosphere changes

Changes from Recycling

Power, staff, structural needs

Fans required for circulation

Atmosphere Model: Calculations



Internal volume * Circulation fans per m^3 = Total number of fans

\# fans * Power required per fan = Total power required by fans

\# fans * Volume required per fan = Total volume required by fans

\# fans * Mass per fan = Total mass of fans

Total mass of fans + Total mass of atmosphere = Total mass for atmosphere model

$-\sum$ O_2 or CO_2 or H_2O changes = O_2 or CO_2 or H2O change required

Key:

- Inputs
- Constants
- Calculated
- Outputs

Atmosphere Model: Results

- Phase 1
  - A significant quantity of atmospheric gas must be shipped up from Earth
  - CO_2 conversion to O_2 required
  - Circulation fans not a significant driver for model output values

Necessary mass (total)	23.8	tonnes
Mass of Atmosphere (Gas only)	23.25	tonnes
Necessary volume	345	m3
Power, Atmosphere	0.17	MW
CO2 change to Recycling	- 115	kg/day
O2 change to Recycling	98	kg/day
H2O change to Recycling	- 230	kg/day
Number of fans	58	#

All values calculated in the model

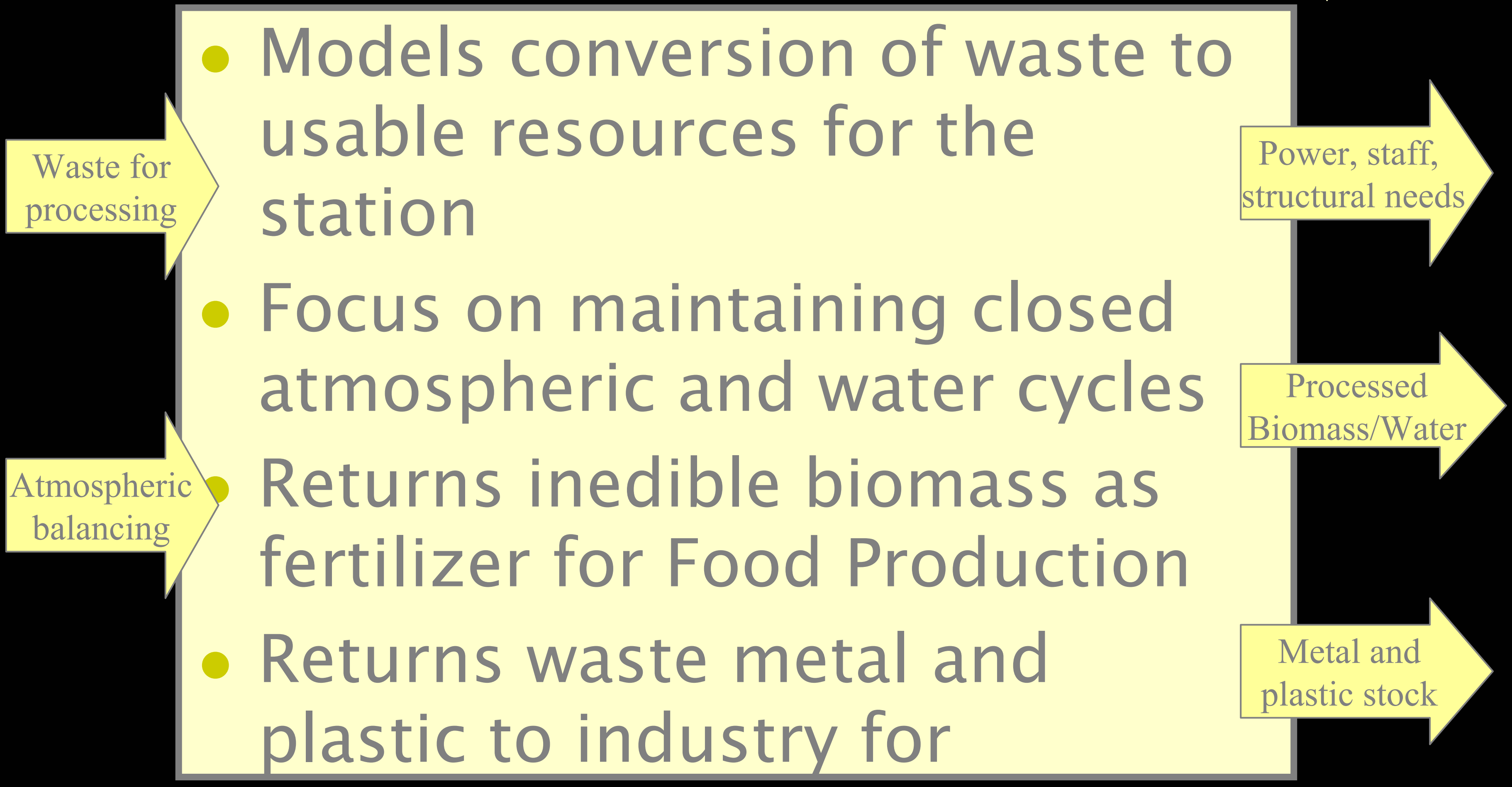
Atmosphere Model: Results

- Phase 4
  - A significant quantity of atmospheric gas must be shipped up from Earth
  - Plant respiration removes more CO_2 than is created elsewhere
  - Circulation fans still not a significant driver for model output values

Necessary mass (total)	2818	tonnes
Mass of Atmosphere (Gas only)	2750	tonnes
Necessary volume	1369	m3
Power, Atmosphere	0.68	MW
CO2 change to Recycling	5766	kg/day
O2 change to Recycling	– 3315	kg/day
H2O change to Recycling	– 5766	kg/day
Number of fans	1790	#

All values calculated in the model

Recycling Model: Overview



Waste for processing

Atmospheric balancing

- Models conversion of waste to usable resources for the station
- Focus on maintaining closed atmospheric and water cycles
- Returns inedible biomass as fertilizer for Food Production
- Returns waste metal and plastic to industry for processing

Power, staff, structural needs

Processed Biomass/Water

Metal and plastic stock

Recycling Model: Assumptions

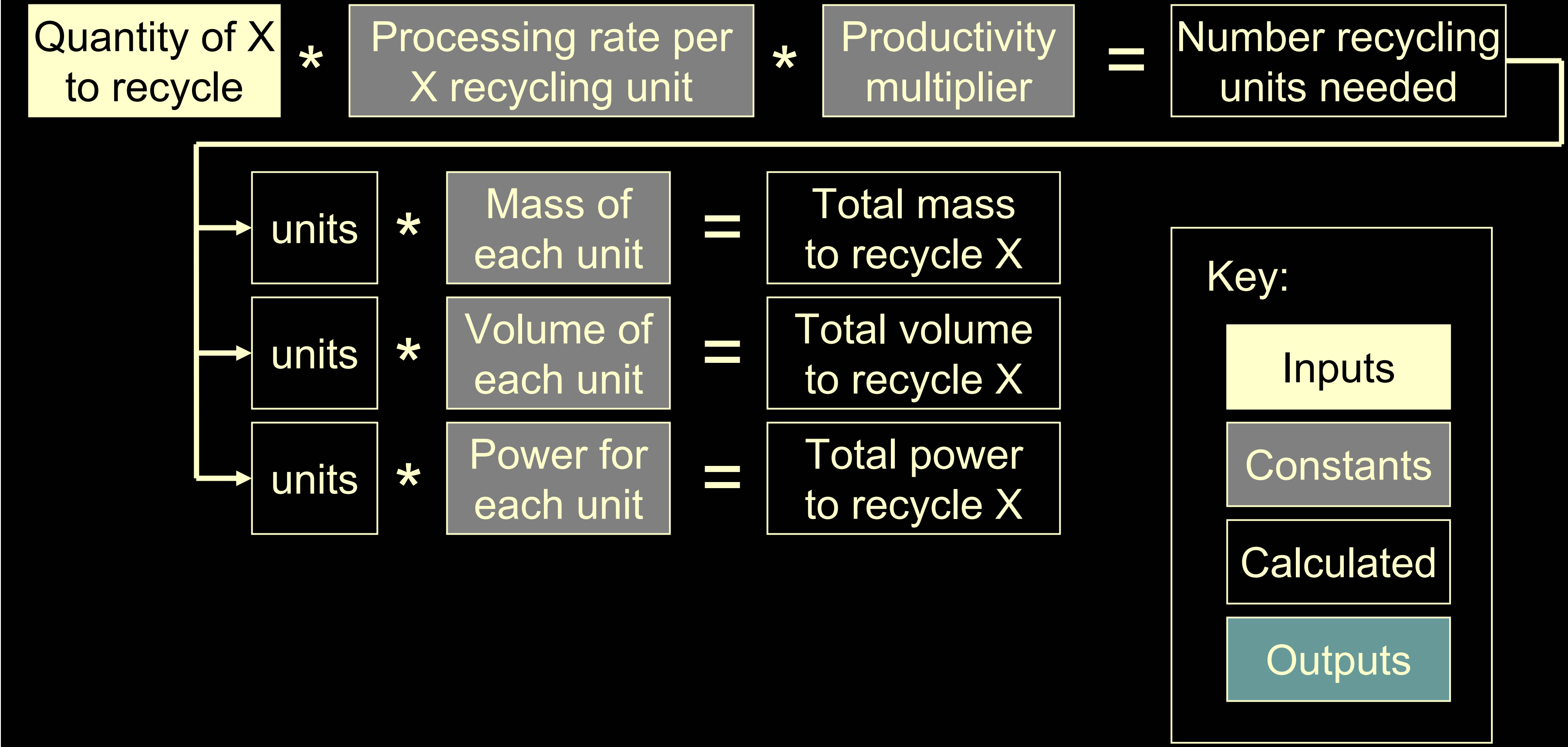
- There will be an increase in efficiency for the various recycling processes due to technological improvements

- Industry can make use of plastic and metal waste recovered from the modules

Phase	Productivity Multiplier
1	1
2	1
3	1.5
4	2

Recycling Model: Calculations

For a given recycled material X, these are the basic calculations for determining model requirements



Quantity of X to recycle * Processing rate per X recycling unit * Productivity multiplier = Number recycling units needed

units * Mass of each unit = Total mass to recycle X

units * Volume of each unit = Total volume to recycle X

units * Power for each unit = Total power to recycle X

Key:

- Inputs
- Constants
- Calculated
- Outputs

Recycling Model: Calculations

- A typical piece of recycling equipment:

  Trace contaminant removal unit* –

  removes contaminants from the atmosphere

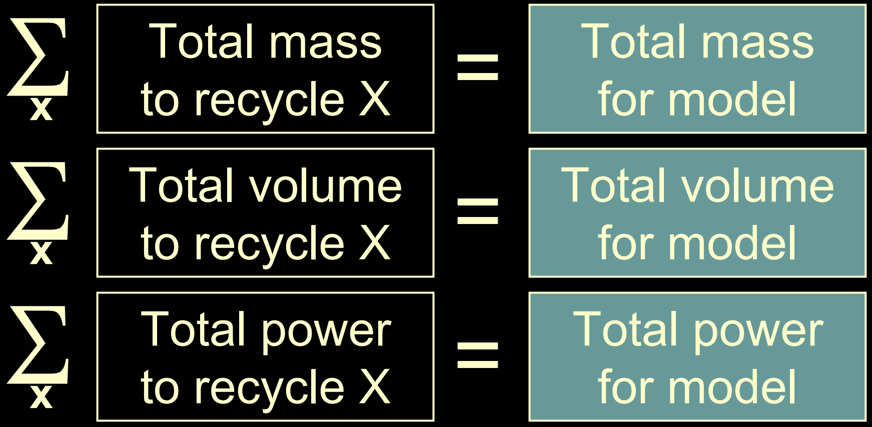
Mass	100	kg
Volume	0.3	m3
Power	150	W
Processing	0.0154	kg/day

Can remove 15.4g/day of contaminants from air

*From *Spaceflight Life Support and Biospherics*

Recycling Model: Calculations

- The calculations for model totals are as follows:



$\sum_x$ Total mass to recycle X = Total mass for model

$\sum_x$ Total volume to recycle X = Total volume for model

$\sum_x$ Total power to recycle X = Total power for model

Key:

- Inputs
- Constants
- Calculated
- Outputs

The calculations for model totals are as follows

Recycling Model: Results

- Phase 1
  - Water processing is the largest task of the model
  - Less significant because operating in only a semi-closed loop
  - Recycling not a significant driver at system level

Necessary mass, Recycling[1]	31.0	tonnes
Metal waste for Recycling[1]	0.2	tonnes/month
Plastic waste for Recycling[1]	0.6	tonnes/month
Fertilizer from Recycling[1]	0	tonnes/month
Power, Recycling[1]	0.04	MW
O2 processed by Recycling[2]	2.9	tonnes/month
H2O processed by Recycling[2]	6.9	tonnes/month
CO2 processed by Recycling[2]	3.5	tonnes/month
Water processed by Recycling[2]	172.5	tonnes/month
Waste from Recycling[1]	1.1	tonnes/month

[1] values calculated in the model

[2] values are inputs

Recycling Model: Results

- Phase 4
  - Water processing is still the largest task of the model
  - Near-closure of life support resource loops
  - Recycling not a significant driver at system level – smaller overall mass percentage

Necessary mass, Recycling[1]	52.1	tonnes
Metal waste for Recycling[1]	7.4	tonnes/month
Plastic waste for Recycling[1]	6.1	tonnes/month
Fertilizer from Recycling[1]	48.5	tonnes/month
Power, Recycling[1]	0.5	MW
O2 processed by Recycling[2]	96.5	tonnes/month
H2O processed by Recycling[2]	12759	tonnes/month
CO2 processed by Recycling[2]	167.9	tonnes/month
Water processed by Recycling[2]	4337	tonnes/month
Waste from Recycling[1]	0.64	tonnes/month

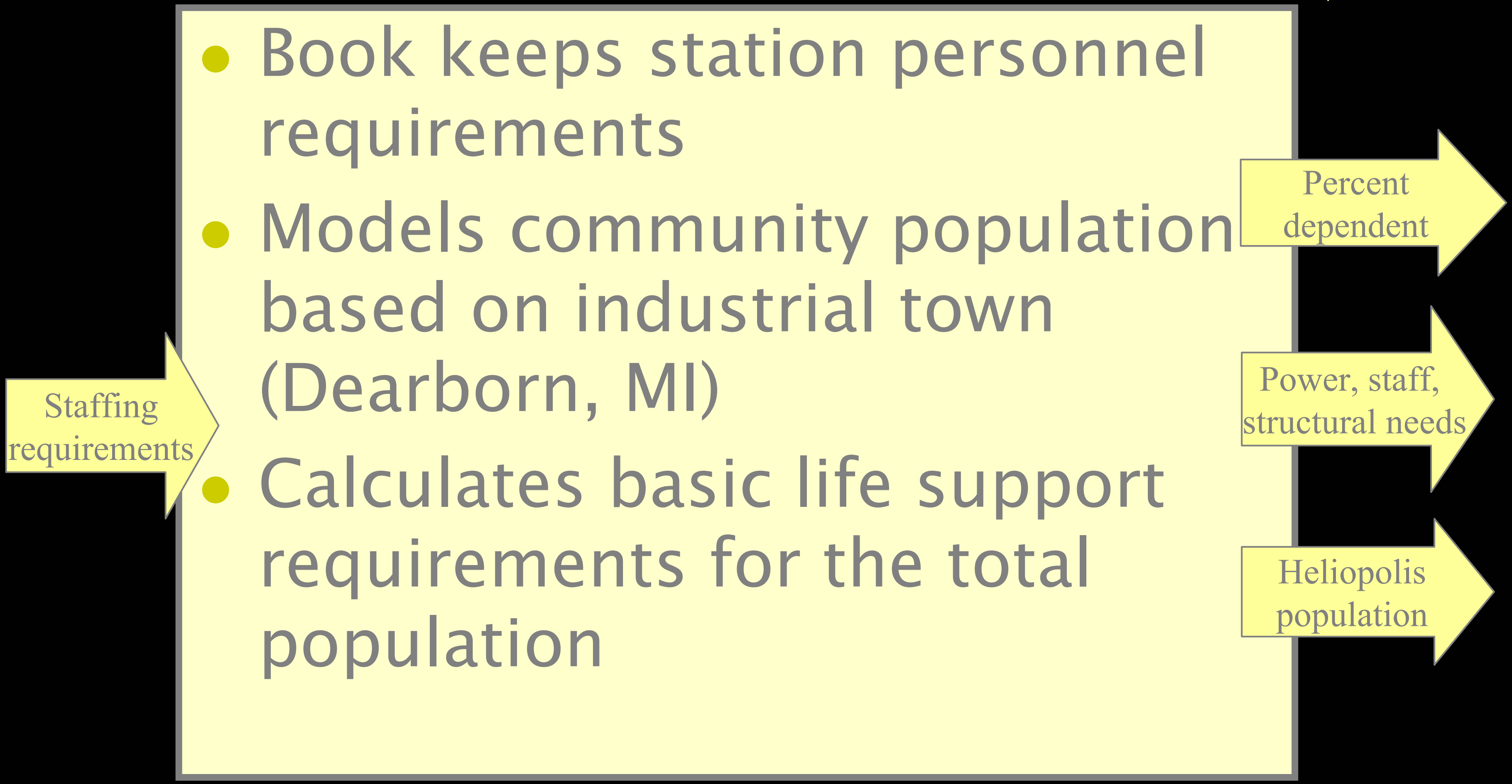
[1] values calculated in the model

[2] values are inputs

Life Support Summary

- Biomass must come from Earth
  - Must pay launch cost for biomass
  - Requires efficient recycling and closed resource loops to be economically feasible
- Can be accomplished with current technology
  - Assumed technological improvements do not greatly reduce the overall mass of the models

Personnel Model: Overview



- Book keeps station personnel requirements
- Models community population based on industrial town (Dearborn, MI)
- Calculates basic life support requirements for the total population

Personnel Model: Assumptions

- In phase 4, there will be a "support" population[1] about 5 times the industrial population[2]
- In phase 4, there non-working dependents will make up about 1/3 of the overall population[3]
- In phase 1, only the necessary people are sent to work on the construction

Phase	Support population fraction	Dependent as fration of working population
1	1.01	0.00
2	1.5	0.18
3	2.75	0.30
4	5	0.50

[1] Industrial population includes Manufacturing, Milling & Primary, Refining and Structures

[2] Based on the Dearborn, MI population

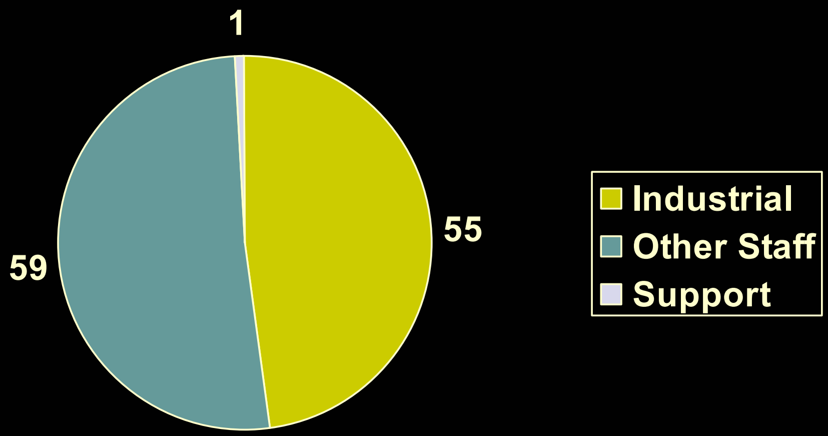
[3] Based on US statistics and adjusted to meet the productivity requirements of the station

Personnel Model: Results

- A fully populated station
  - Majority work as support population for industry
  - Non-working family next largest group
  - Food production third largest
  - Actual industry personnel fourth largest
  - Station maintenance personnel smallest group

Personnel Model: Results

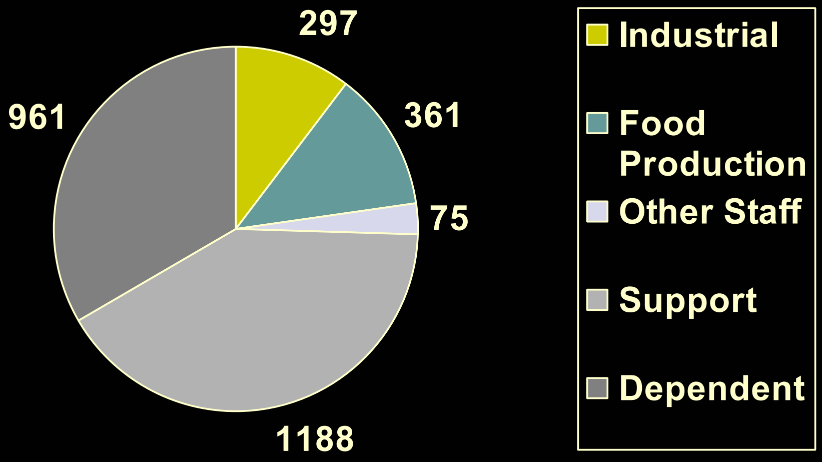
- Phase 1 population breakdown



Staff, Attitude/Orbit	5
Staff, Food Production	0
Staff, Manufacturing	29
Staff, Milling & Primary	22
Staff, Power	9
Staff, Radiation Shielding	1
Staff, Recycling	3
Staff, Refining	4
Staff, Structures	0
Staff, Thermal	25
Staff, Transportation	15
Subtotal of Station Staff	113
Staff, Personnel	1
Support population for Industry	1
Total Working	115
Total Non-working	0
Total Personnel	115

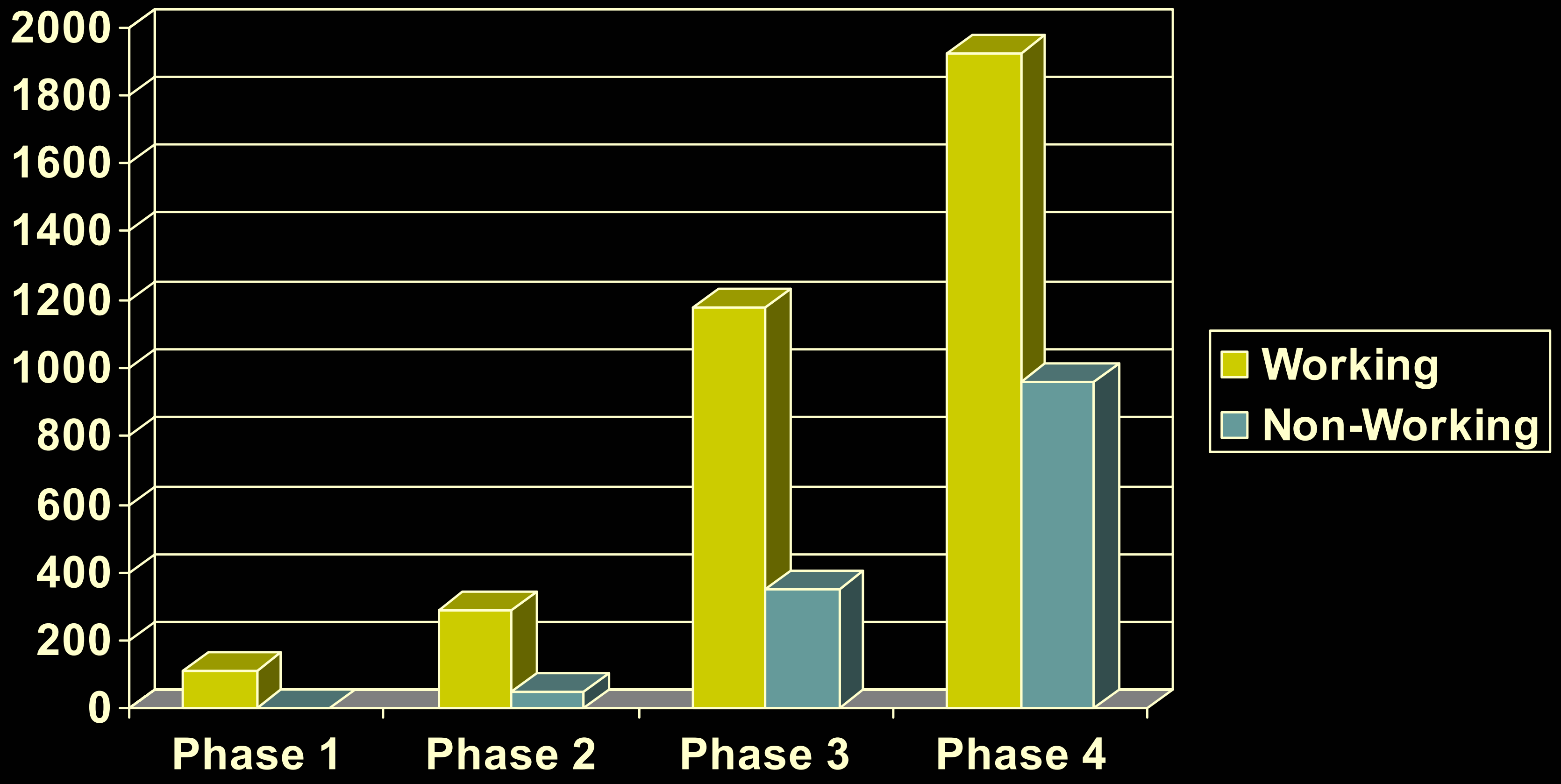
Personnel Model: Results

- Phase 4 population breakdown

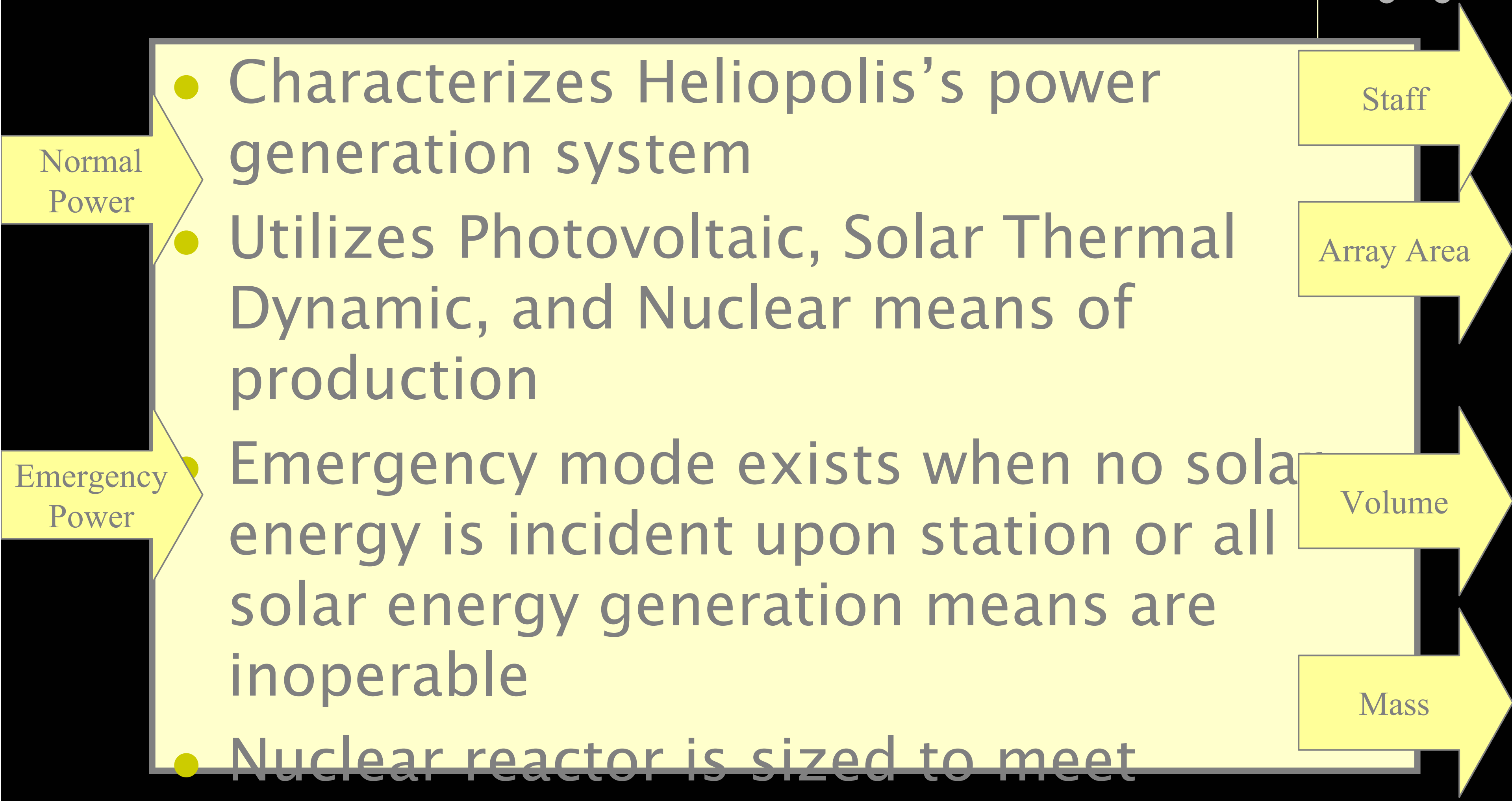


Staff, Attitude/Orbit	5
Staff, Food Production	361
Staff, Manufacturing	246
Staff, Milling & Primary	35
Staff, Power	26
Staff, Radiation Shielding	5
Staff, Recycling	6
Staff, Refining	14
Staff, Structures	2
Staff, Thermal	17
Staff, Transportation	15
Subtotal of Station Staff	732
Staff, Personnel	1
Support population for Industry	1188
Total Working	1921
Total Non-working	961
Total Personnel	2882

Personnel Model: Results



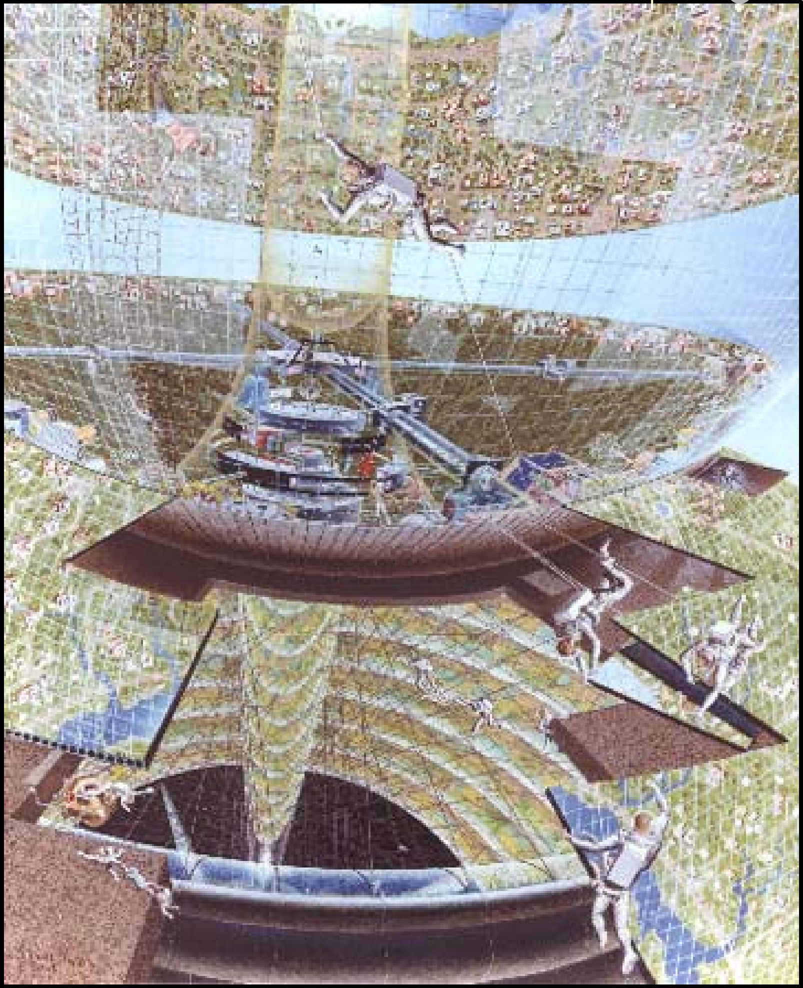
Power Model



- Characterizes Heliopolis's power generation system
- Utilizes Photovoltaic, Solar Thermal Dynamic, and Nuclear means of production
- Emergency mode exists when no solar energy is incident upon station or all solar energy generation means are inoperable
- Nuclear reactor is sized to meet emergency requirements

Power Assumptions

- Solar Photovoltaic
  - 10 fold power/mass improvement by fourth phase
  - 75% power produced
- Solar Thermal Dynamic
  - 6 fold power/mass improvement by fourth phase
  - 20% of power produced
- Nuclear
  - 6 fold power/mass improvement by fourth phase
  - 5% of power produced
  - Sized to meet emergency power demands



Power Model Notes

- Features of each phases power generation method are shown along with the power subsystems results summary for each phase in a table and chart to follow

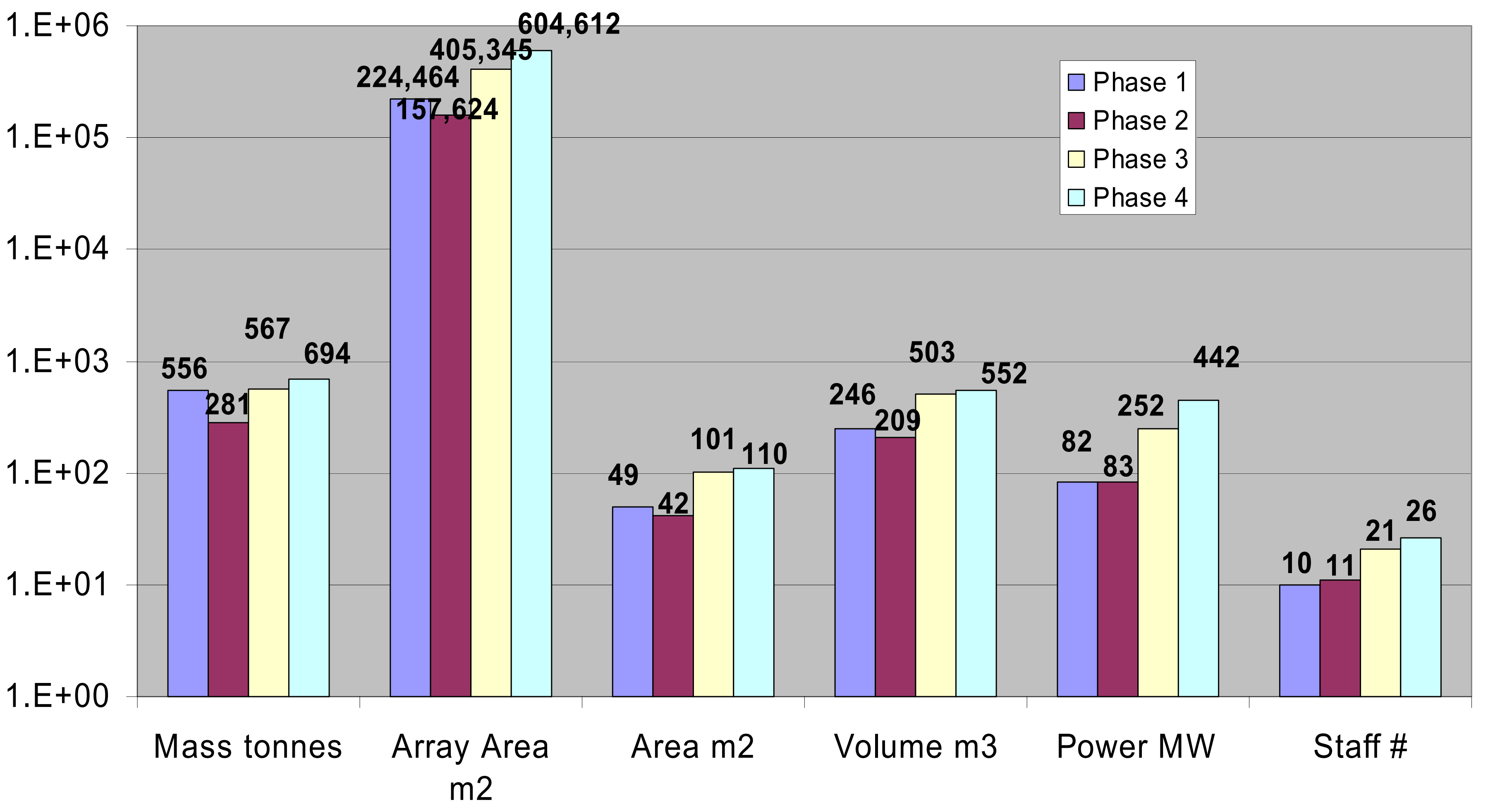
*Inflatable Solar Thermal Dynamic Example

Power Assumptions

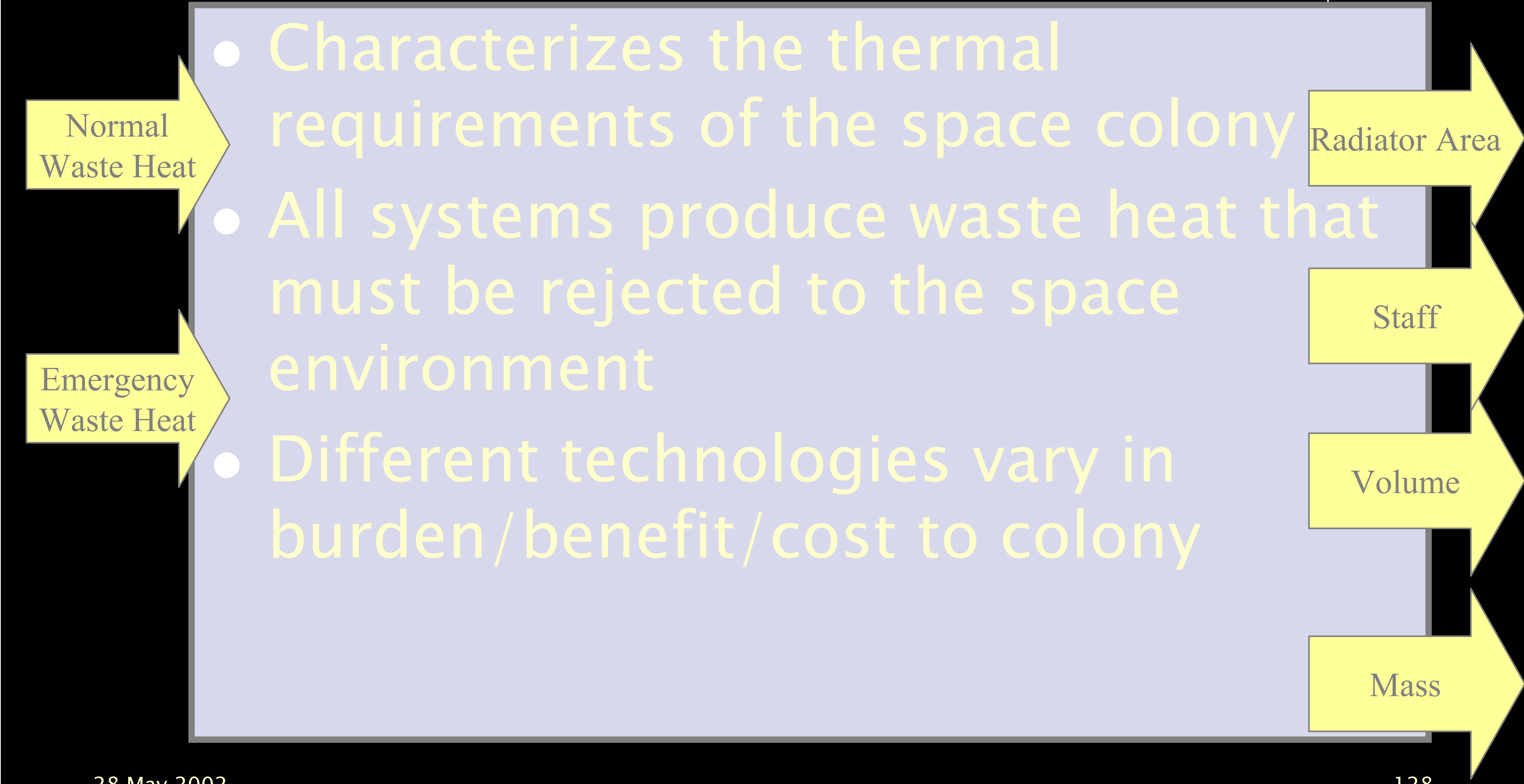
Power Generation Options		mass	volume	area	Staff
		kg/MW	m^3/MW	m^2/MW	pps/MW
Phase 1	Photovoltaic	5000.00	72.99	3649.64	0.10
Phase 2	Photovoltaic	2500.00	60.83	3041.36	0.10
Phase 3	Photovoltaic	1000.00	47.09	2354.60	0.07
Phase 4	Photovoltaic	500.00	36.50	1824.82	0.048
Phase 1	Dynamic	6000.00	19.23	1923.08	0.12
Phase 2	Dynamic	3000.00	15.38	1538.46	0.14
Phase 3	Dynamic	1500.00	12.82	1282.05	0.10
Phase 4	Dynamic	1000.00	10.99	1098.90	0.07
Phase 1	Nuclear	12500.00	60.00	12.00	0.16
Phase 2	Nuclear	6000.00	50.00	10.00	0.19
Phase 3	Nuclear	4000.00	40.00	8.00	0.14
Phase 4	Nuclear	2000.00	25.00	5.00	0.09

Phase 1 values from SMAAD later phases follow from reasonable technology roadmap

Power Model Results Summary



Thermal Model



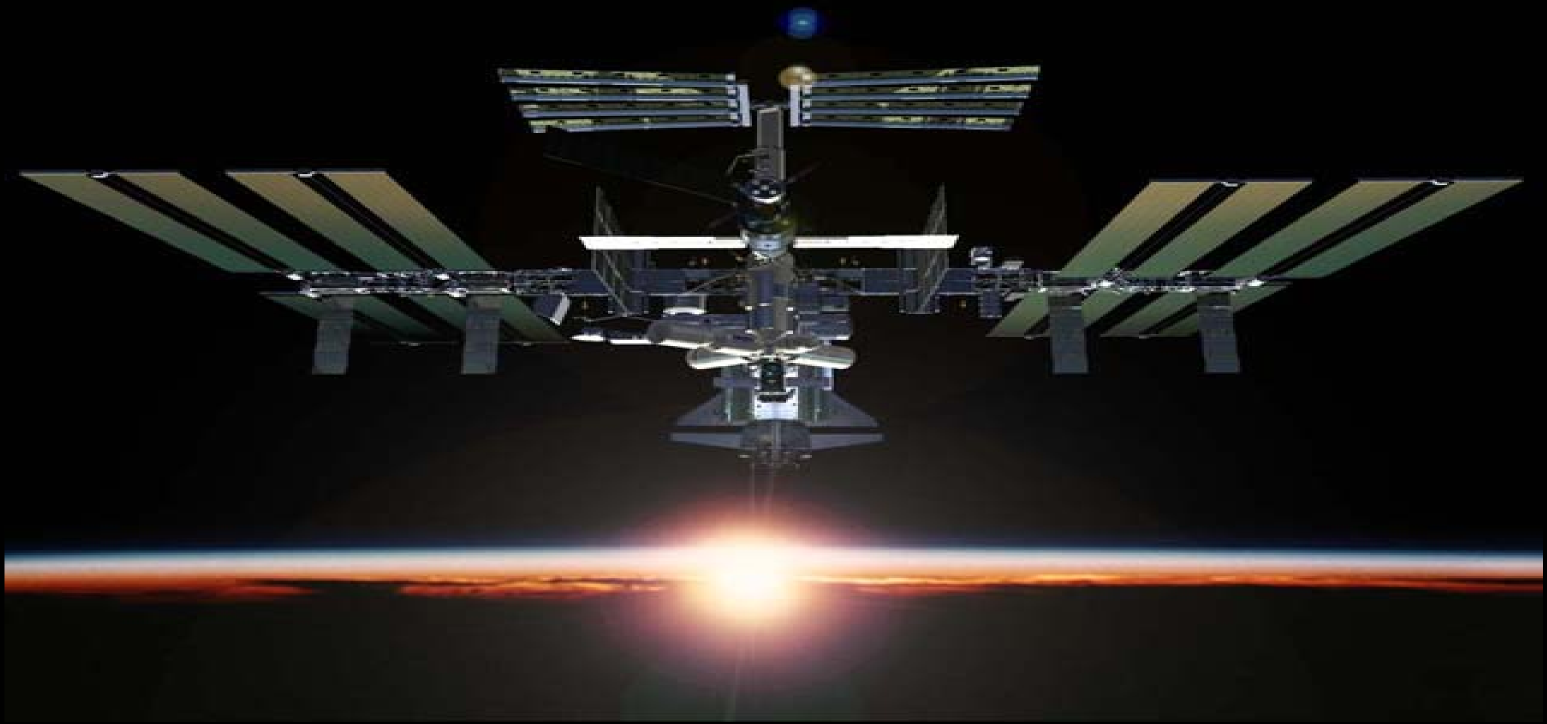
- Characterizes the thermal requirements of the space colony
- All systems produce waste heat that must be rejected to the space environment
- Different technologies vary in burden/benefit/cost to colony

Thermal Assumptions

- Radiator
  - 100 fold improvement in heat rejected per mass by fourth phase
  - Removes 60% of waste heat
  - Large area required for array
- Heat Pipes
  - 10 fold improvement in heat rejected per mass by fourth phase
  - Removes 20% of waste heat
  - No power required, but limited by available area
- Regenerative
  - 10 fold improvement in heat rejected per mass by fourth phase
  - Removes 20% of waste heat
  - Produce power from high energy waste heat

Thermal Model Notes

- Features of each phases thermal control method are shown along with the thermal subsystems results summary in a table and chart to follow

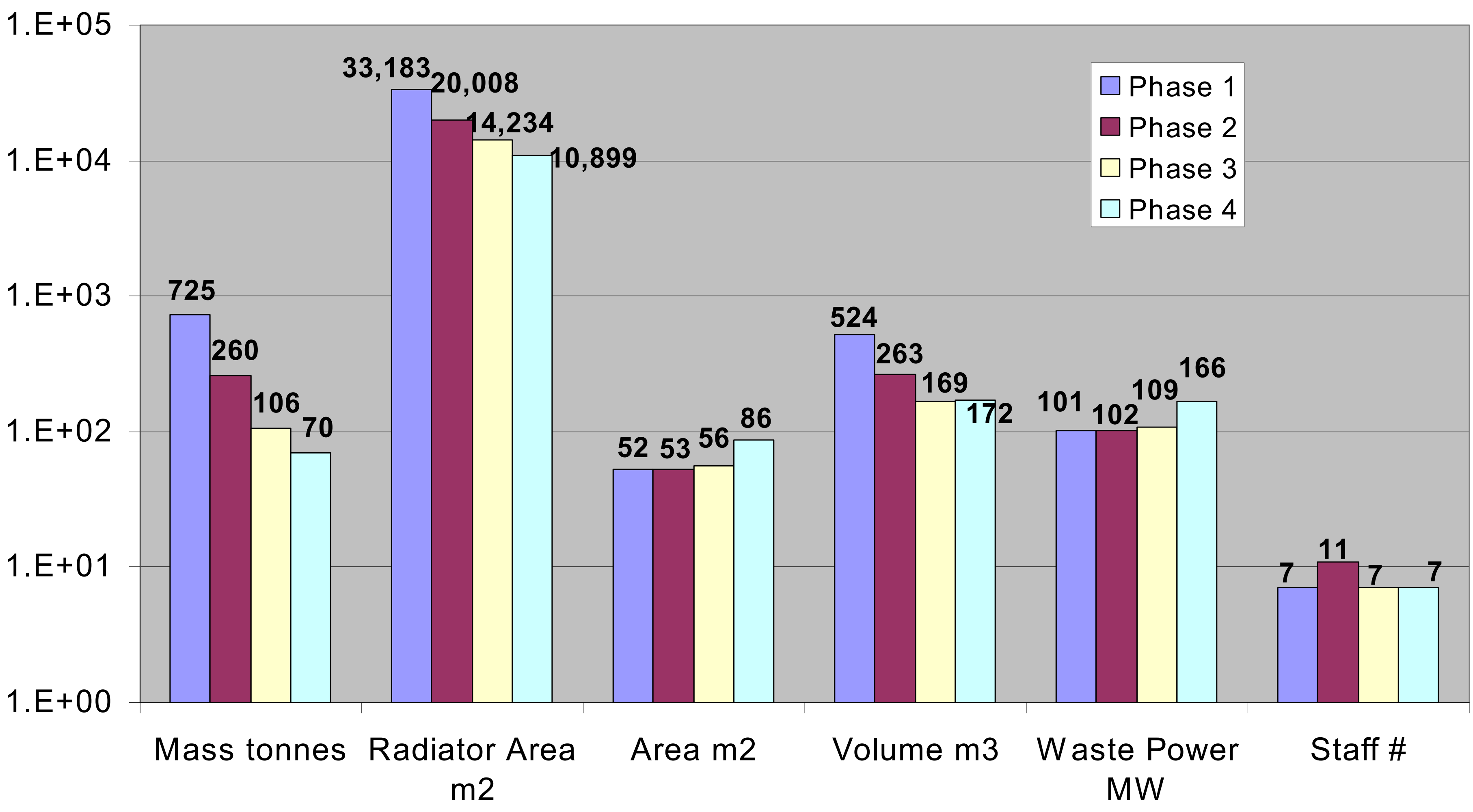


Thermal Assumptions

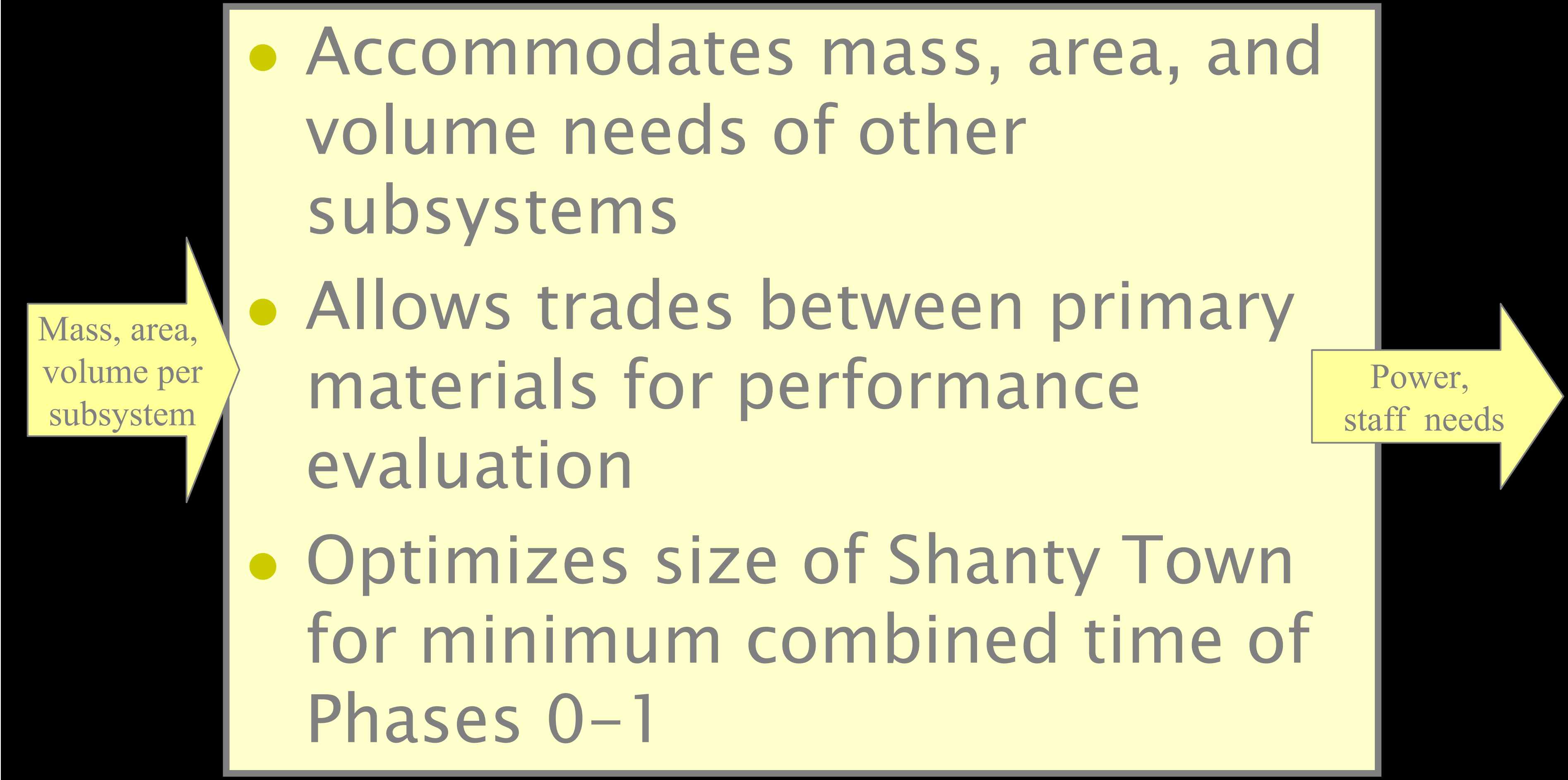
Thermal Control Options		mass	volume	area	power	staff
		kg/MW	m^3/MW	m^2/MW	MW/MW	pps/MW
Phase 1	Radiator	5000	10	500	0.01	0.04
Phase 2	Radiator	1000	6	300	0.01	0.08
Phase 3	Radiator	300	4	200	0.01	0.05
Phase 4	Radiator	50	2	100	0.01	0.03
Phase 1	Heat Pipes	2500	0.1	1000	0	0.001
Phase 2	Heat Pipes	1000	0.06	600	0	0.001
Phase 3	Heat Pipes	500	0.03	300	0	0.001
Phase 4	Heat Pipes	250	0.015	150	0	0.001
Phase 1	Regenerative	20000	30	3	-0.2	0.12
Phase 2	Regenerative	10000	15	3	-0.2	0.2
Phase 3	Regenerative	4000	9	3	-0.2	0.1
Phase 4	Regenerative	2000	6	3	-0.2	0.05

Phase 1 values from SMAAD later phases follow from reasonable technology roadmap

Thermal Model Results Summary



Structures: Overview



Mass, area, volume per subsystem

- Accommodates mass, area, and volume needs of other subsystems
- Allows trades between primary materials for performance evaluation
- Optimizes size of Shanty Town for minimum combined time of Phases 0–1

Power, staff needs

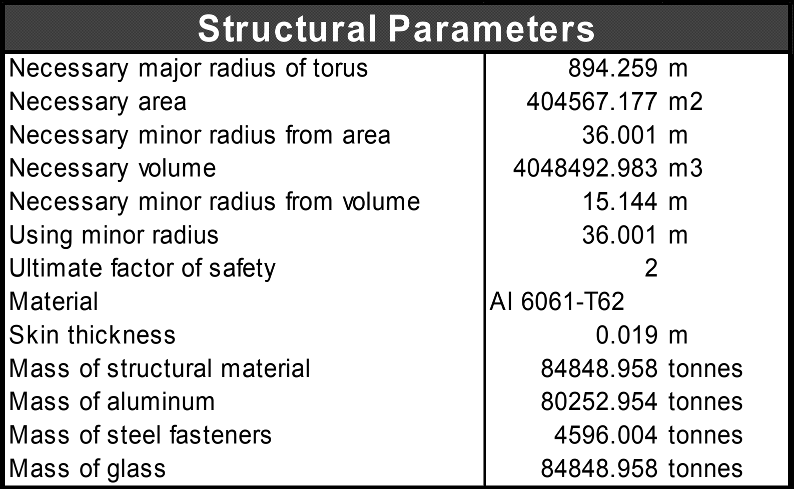
Structures: Example

MASS	
In Outer Torus	
Atmosphere	1162 tonnes
Attitude & Orbit	7 tonnes
Habitat	12487104 tonnes
Personnel	481 tonnes
Recycling	114 tonnes
Thermal (internal)	3336 tonnes
Transportation	100 tonnes
In Inner Torus	
Food Production	49619.87 tonnes
Out of Plane	
Manufacturing	57492 tonnes
Milling & Primary	1848 tonnes
Power (not solar panels)	603.3 tonnes
Radiator	87.5 tonnes
Refining	33049 tonnes
Solar Panels	2154.5 tonnes
Thermal (external)	1086.3 tonnes

AREA	
In Outer Torus	
Atmosphere	0 m2
Attitude & Orbit	106 m2
Habitat	1815168 m2
Personnel	0 m2
Recycling	823 m2
Thermal (internal)	728808 m2
Transportation	10000 m2
In Inner Torus	
Food Production	132563.4 m2
Out of Plane	
Manufacturing	3481 m2
Milling & Primary	243 m2
Power (not solar panels)	503 m2
Radiator	0 m2
Refining	32631 m2
Solar Panels	3194074 m2
Thermal (external)	243021 m2

- An example of the mass accounting budget

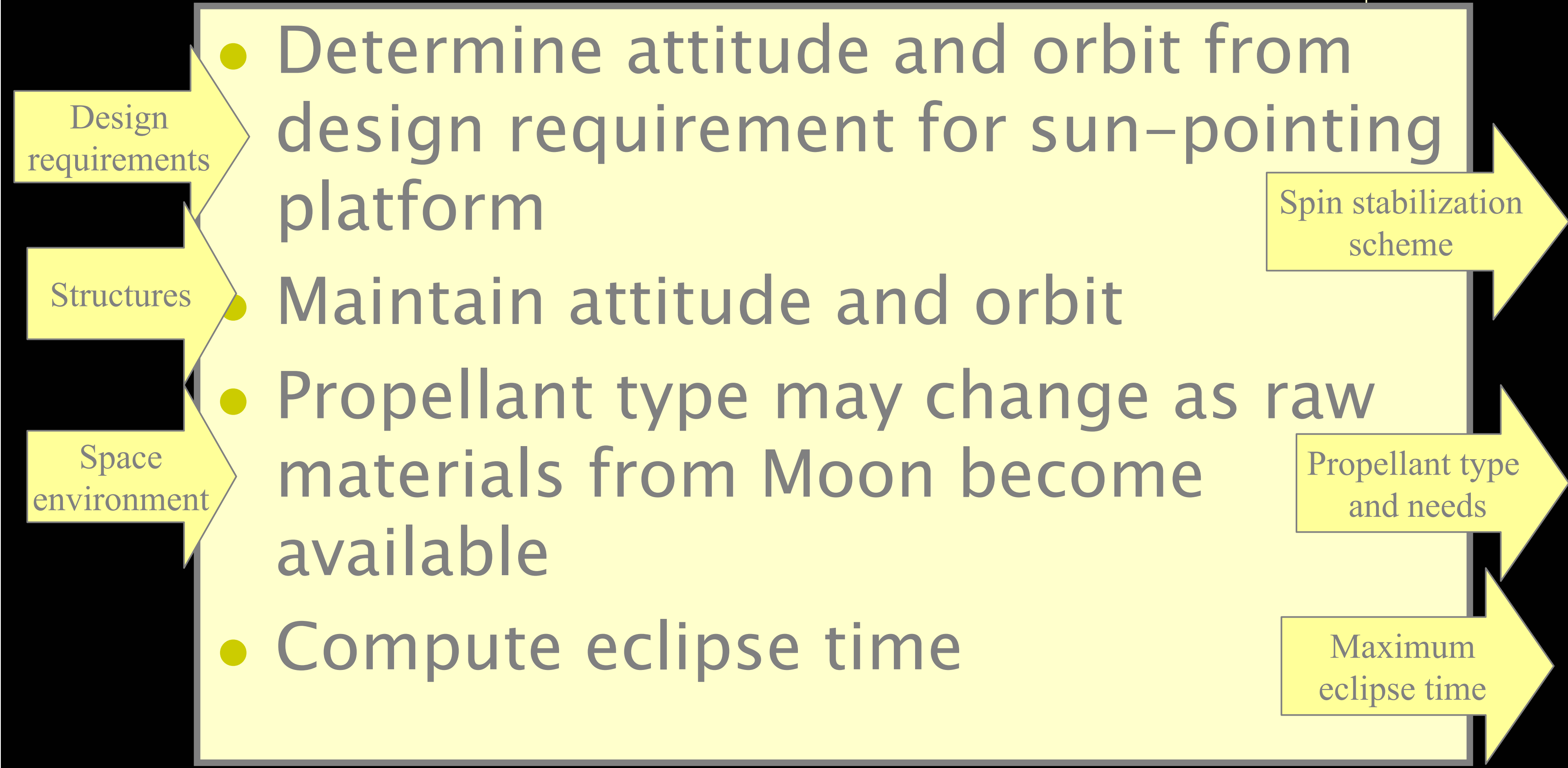
Structures



Structural Parameters		
Necessary major radius of torus	894.259	m
Necessary area	404567.177	m2
Necessary minor radius from area	36.001	m
Necessary volume	4048492.983	m3
Necessary minor radius from volume	15.144	m
Using minor radius	36.001	m
Ultimate factor of safety	2	
Material	Al 6061-T62	
Skin thickness	0.019	m
Mass of structural material	84848.958	tonnes
Mass of aluminum	80252.954	tonnes
Mass of steel fasteners	4596.004	tonnes
Mass of glass	84848.958	tonnes

- Calculations for structure size, amount of material needed
- Uses a database of material properties
- Plausible comparison with 1975 Stanford study

Attitude & Orbit



Design requirements

Structures

Space environment

- Determine attitude and orbit from design requirement for sun-pointing platform
- Maintain attitude and orbit
- Propellant type may change as raw materials from Moon become available
- Compute eclipse time

Spin stabilization scheme

Propellant type and needs

Maximum eclipse time

Attitude & Orbit

- Orbital perturbations (Heliopolis, Phase 4)
  - Solar radiation pressure
    - 0.93 N
  - L1 orbital instability
    - 0.076 N

$$F_a \approx \tfrac{1}{2}\rho C_d A_t V^2,\ \rho = \text{density},\ C_d = 2.2$$

$$A_t = \text{area tangent to orbit},\ V = \text{orbital velocity}$$

$$F_{sp} \approx \tfrac{S}{c} A_n (1+q)\cos(i),\quad q \approx 0.6,\quad \cos(i) \approx 1,$$

$$S = 1358\ \text{W/m}^2, \text{solar flux at 1 AU from the Sun,}$$

$$A_n = \text{area normal to orbit plane},\ c = 3\times 10^8\ \text{m/s}$$

- Propellant to counter forces and maintain orbital stability
  - **0.0533 tonnes/month (Xe)**
  - Assumes Isp = 5000 for Solar Powered Xenon Ion Propulsion (Phase 4)

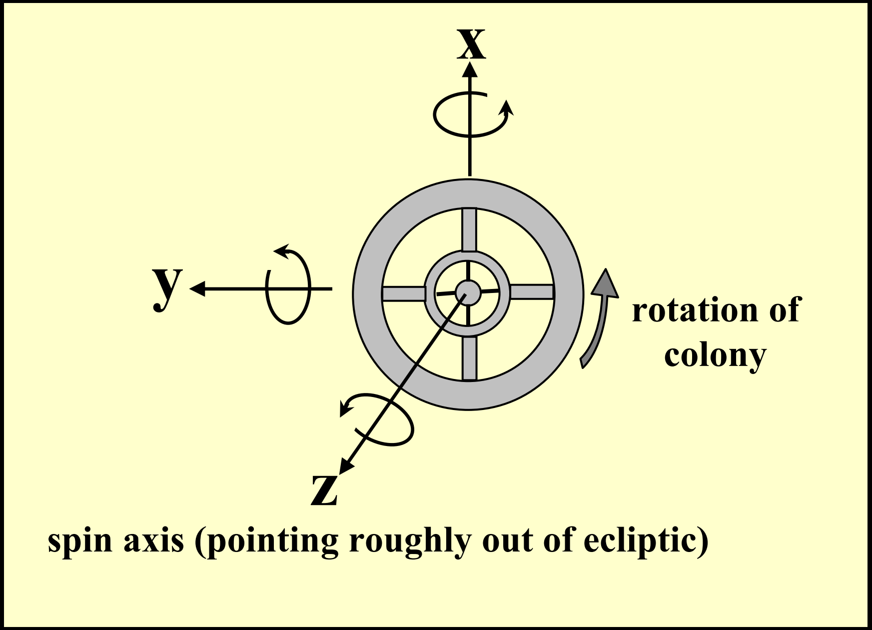
$$\frac{dm_p}{dt} \approx \frac{\rho r C_d A_t}{2 I_{sp}} \quad \text{for aerodynamic drag}$$

$$\frac{dm_p}{dt} \approx \frac{F_{sp}}{g I_{sp}} \quad \text{for solar radiation pressure}$$

- Power needed: **0.0288 MW**

Attitude & Orbit

- Euler angles
  - (pitch, yaw, roll) = (θ,ϕ,ψ)
- Rotation rates
  - ω_z = **1 rpm**
  - $\omega_x = \omega_y = 0$



Attitude & Orbit

- Moments of inertia for an *n* concentric torus structure

$$I_2 = (\tfrac{3}{2} st + r^2) M$$

$$I_1 = I_3 = (\tfrac{5}{4} st + \tfrac{1}{2} r^2) M$$

where:

$r =$ major radius, $s =$ minor radius

$t =$ skin thickness, $M =$ mass of torus.

Notice: $I_2 \approx 2 I_1$ when $st << r^2$

For n concentric tori with moments I_1^a, I_2^a, and I_3^a, where $a = 1, \ldots, n$,

we simply sum:

$$I_i = \sum_{a=1}^{n} I_i^a, \quad \text{for } i = 1,2,3$$

Attitude & Orbit

- Torque estimates
  - Gravity gradient

$$T_g \approx \tfrac{3\mu}{R^3}\,|\,I_3 - I_2\,|\,\psi,\quad \psi = \text{deviation from vertical},$$
$$\mu = \mathrm{GM_E},\ R = \text{radius of orbit}$$

  - Aerodynamic

$$T_a \approx F_a \delta c_g,\ \frac{\delta c_g}{L} = 1\%,\ L \approx 895\text{m}$$

  - Solar radiation pressure

$$T_{sp} \approx F_{sp} \delta c_g$$

  - Magnetic field

$$T_m \approx DB,\ D = \text{residual dipole moment of vehicle},$$
$$B = \tfrac{2M}{R^3},\ M = 7.96\times 10^{15}\,\text{tesla m}^3$$

Attitude & Orbit

- Torque estimates for Heliopolis, Phase 4

Gravity gradient	0.005 Nm per deg of ψ
Aerodynamic	~0
Solar radiation pressure	8.34 Nm per 1% of δc_g
Magnetic field	~0

Attitude & Orbit

- **Attitude stabilization**
  - **Spin stabilization** (for torques affecting z axis)
    - For 1° accuracy Hss = T*P/4 , P = orbit period
    - Hss = 2.99e8 kg m^2/s (for T = Tsp , SRP)[1]
    - H = 1.71e10 kg m^2/s >> Hss
  - **Thruster stabilization** (for torques affecting x,y axes)
    - Disturbance torque: T = Tsp , SRP
    - Thrust needed: Th = T/L , L = length of arm (torus major axis)
    - dm/dt = Th / (g * Isp) = 4.93e-4 tonnes/month of xenon

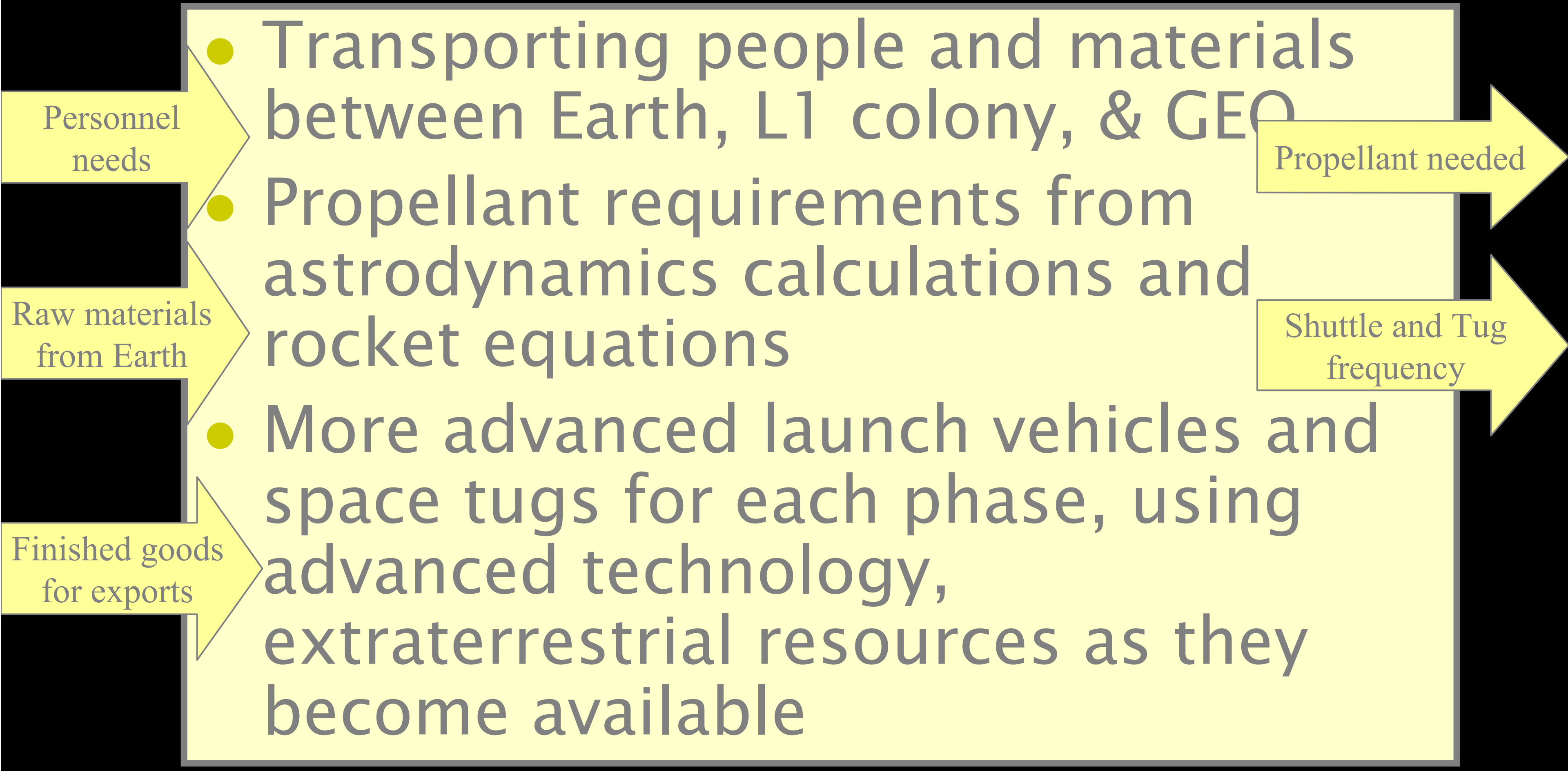
[1] Worst case torque

Attitude & Orbit

- Eclipses
  - Very rare in Lunar L1 halo orbit

- Conclusions
  - Solar radiation pressure is dominant perturbation
  - Solar powered xenon ion propulsion is adequate
  - For attitude maintenance, spin stabilization with a few thrusters is adequate

Transportation



Personnel needs

Raw materials from Earth

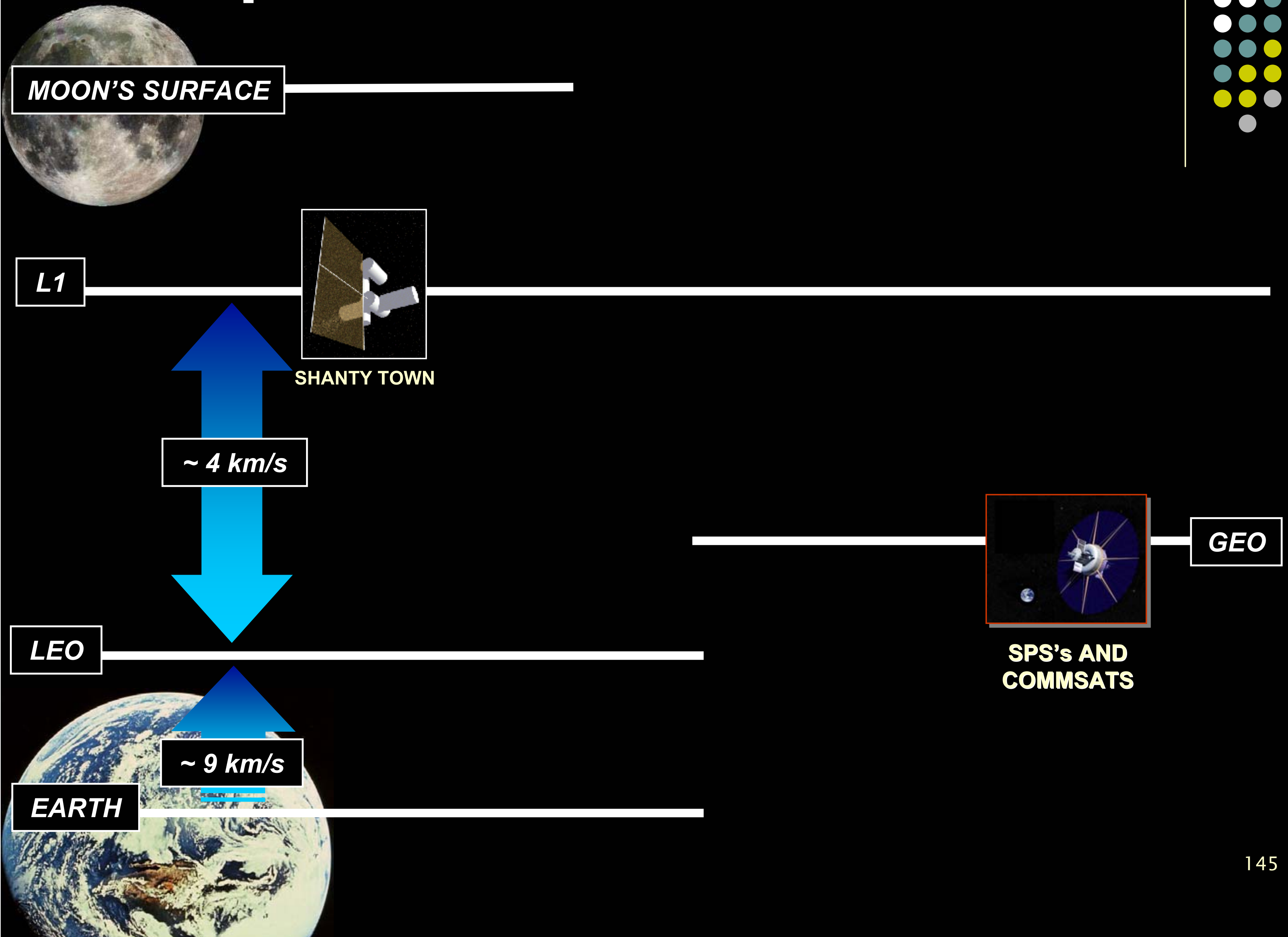
Finished goods for exports

- Transporting people and materials between Earth, L1 colony, & GEO
- Propellant requirements from astrodynamics calculations and rocket equations
- More advanced launch vehicles and space tugs for each phase, using advanced technology, extraterrestrial resources as they become available

Propellant needed

Shuttle and Tug frequency

Transportation: Overview



MOON'S SURFACE

L1

SHANTY TOWN

~ 4 km/s

GEO

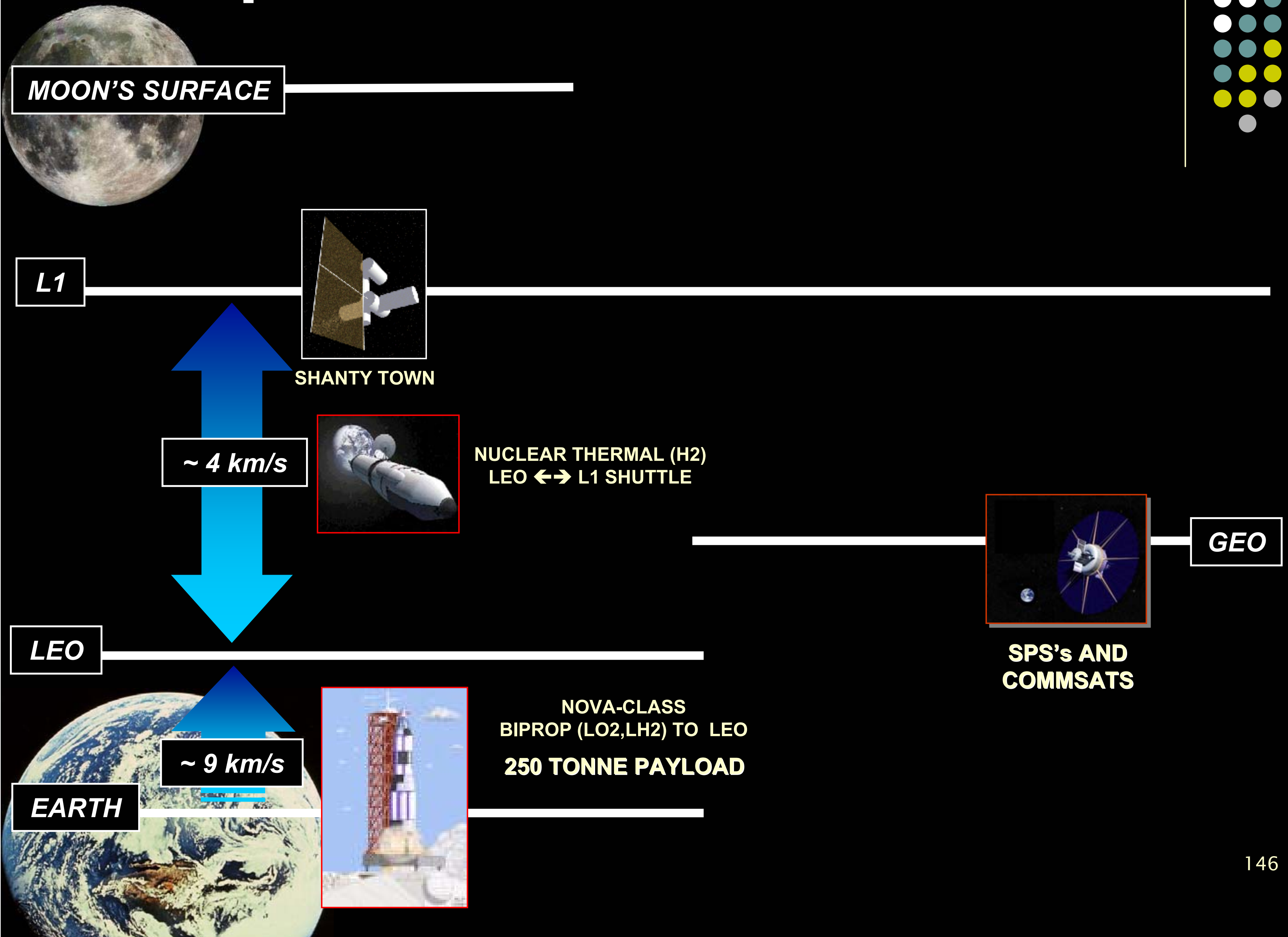
SPS's AND COMMSATS

LEO

~ 9 km/s

EARTH

Transportation: Overview



MOON'S SURFACE

L1

SHANTY TOWN

~ 4 km/s

NUCLEAR THERMAL (H2)
LEO ←→ L1 SHUTTLE

GEO

SPS's AND
COMMSATS

LEO

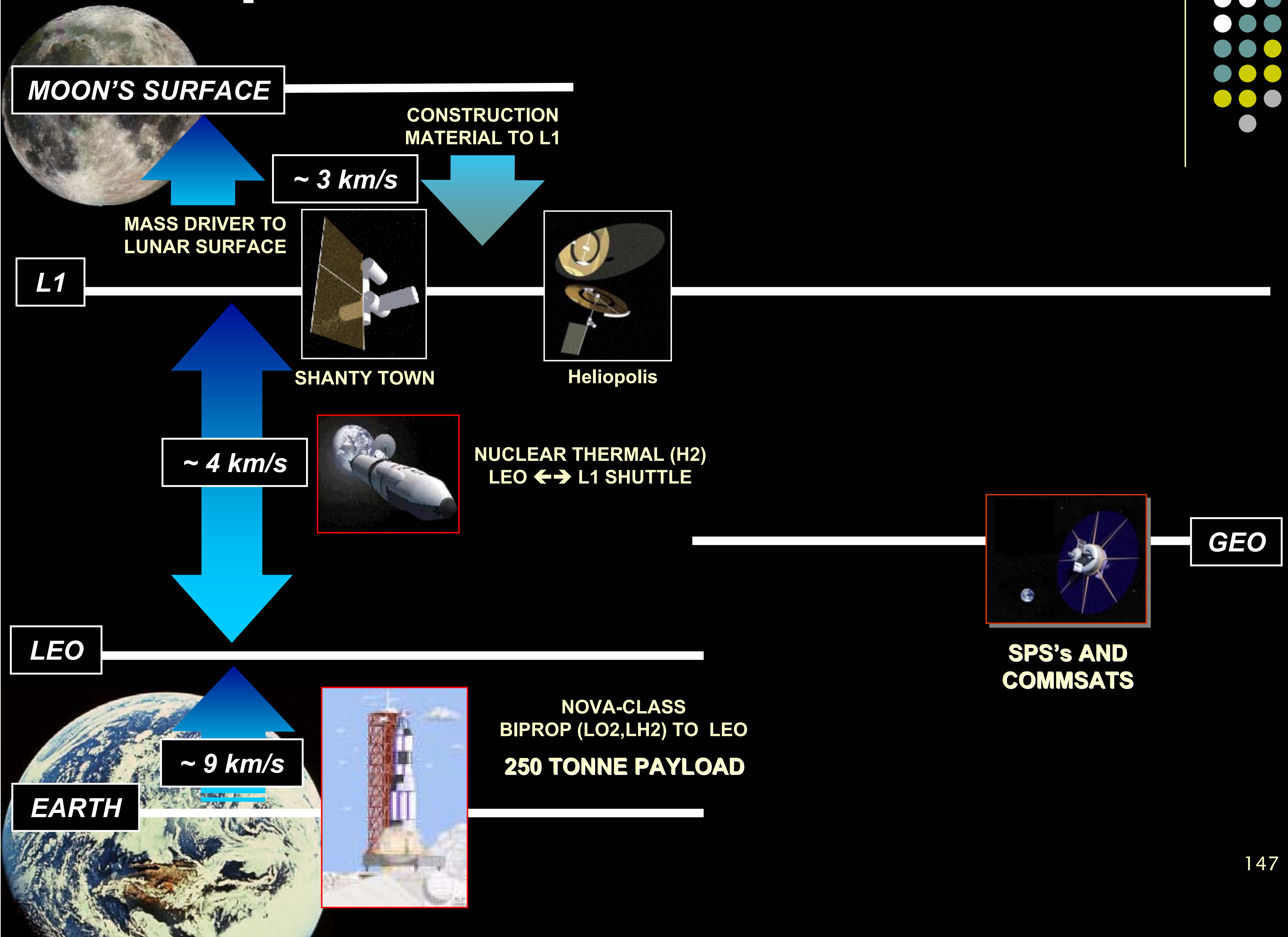
~ 9 km/s

EARTH

NOVA-CLASS
BIPROP (LO2,LH2) TO LEO

250 TONNE PAYLOAD

Transportation: Overview



MOON'S SURFACE

CONSTRUCTION MATERIAL TO L1

~ 3 km/s

MASS DRIVER TO LUNAR SURFACE

L1

SHANTY TOWN

Heliopolis

~ 4 km/s

NUCLEAR THERMAL (H2)
LEO ←→ L1 SHUTTLE

GEO

SPS's AND COMMSATS

LEO

NOVA-CLASS
BIPROP (LO2,LH2) TO LEO

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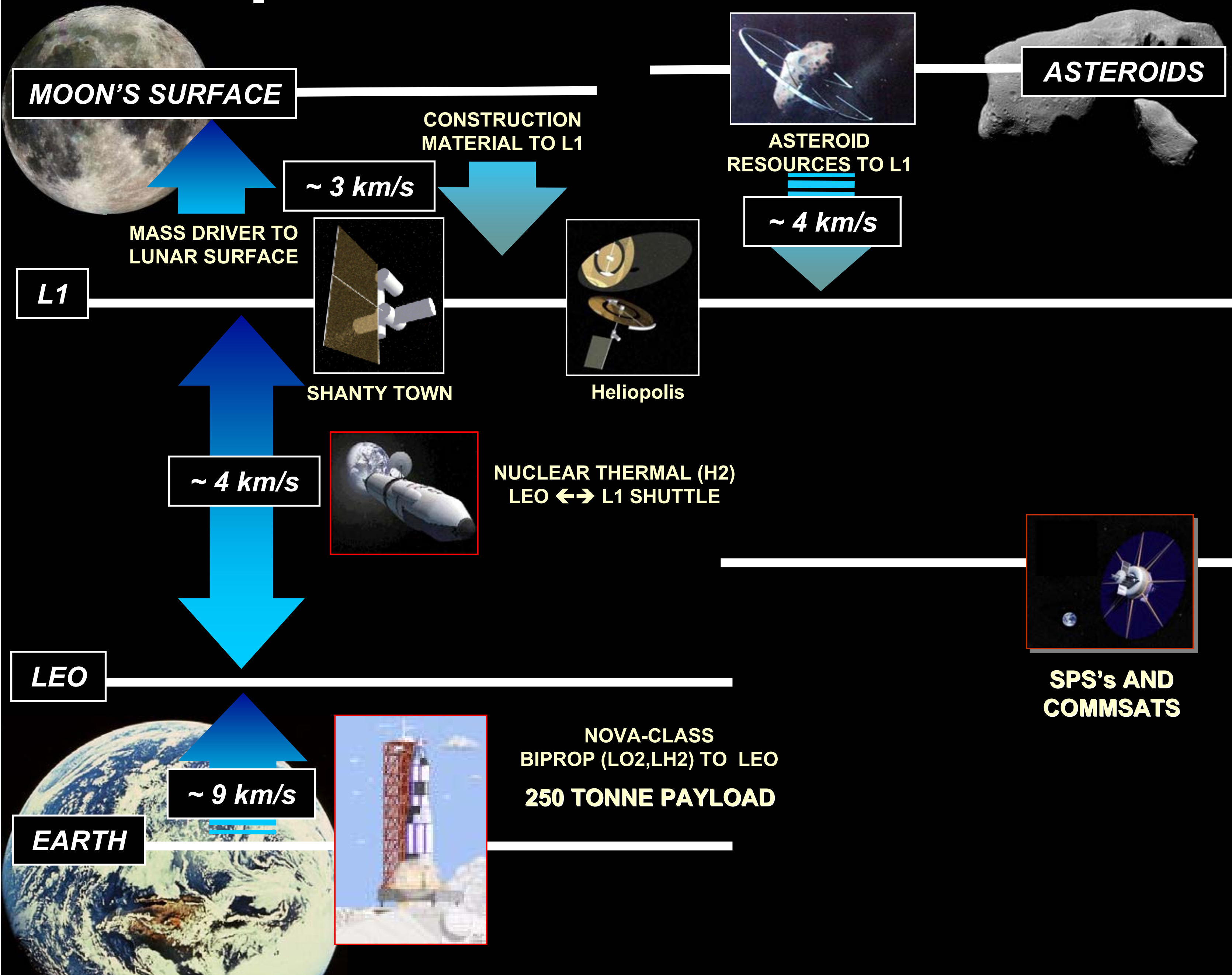
~ 9 km/s

EARTH

Transportation: Overview



MOON'S SURFACE

ASTEROIDS

CONSTRUCTION MATERIAL TO L1

ASTEROID RESOURCES TO L1

~ 3 km/s

~ 4 km/s

MASS DRIVER TO LUNAR SURFACE

L1

SHANTY TOWN

Heliopolis

~ 4 km/s

NUCLEAR THERMAL (H2)
LEO ←→ L1 SHUTTLE

GEO

SPS's AND COMMSATS

LEO

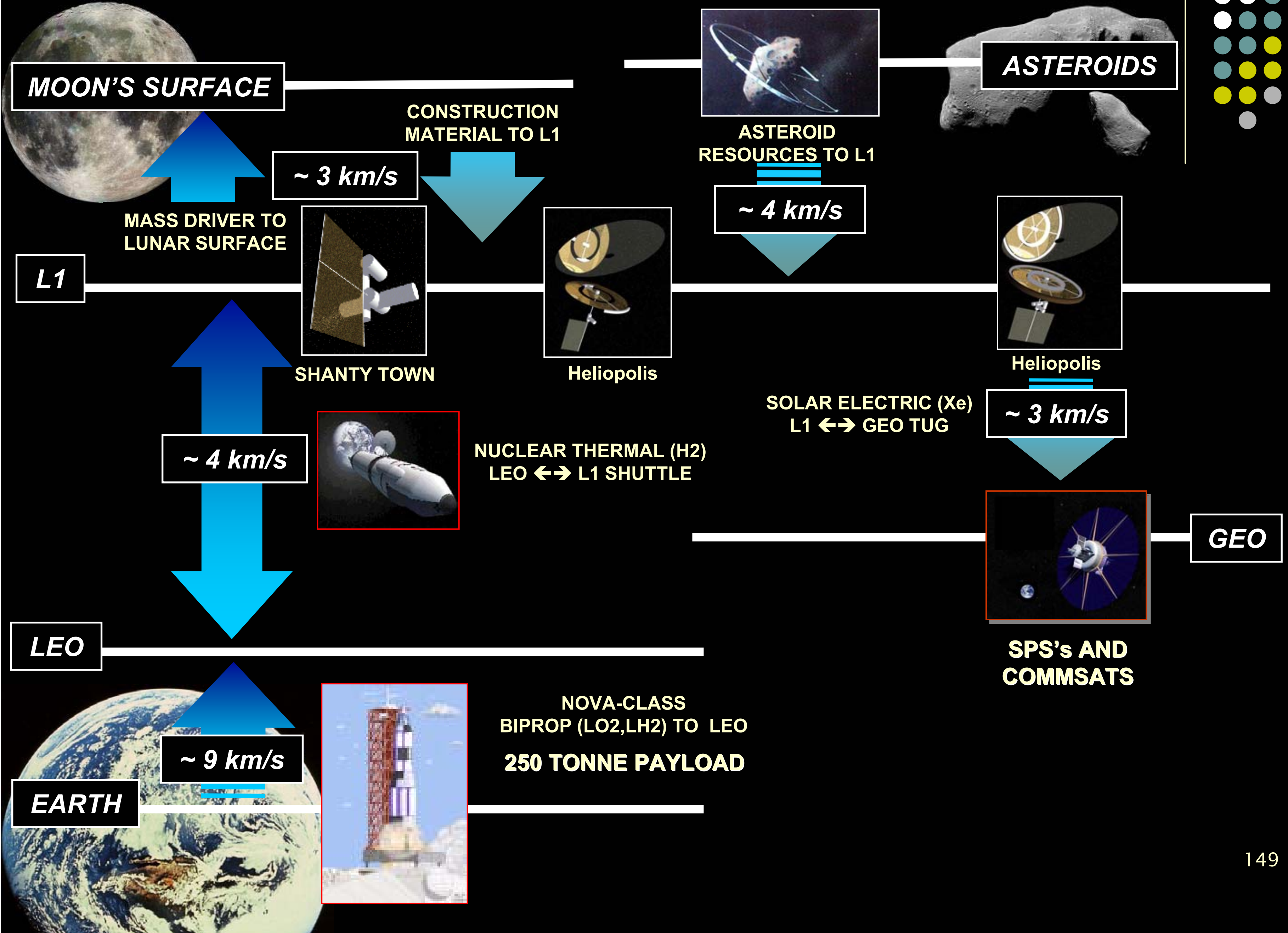
~ 9 km/s

EARTH

NOVA-CLASS
BIPROP (LO2,LH2) TO LEO

250 TONNE PAYLOAD

Transportation: Overview



MOON'S SURFACE

ASTEROIDS

CONSTRUCTION MATERIAL TO L1

ASTEROID RESOURCES TO L1

~ 3 km/s

~ 4 km/s

MASS DRIVER TO LUNAR SURFACE

L1

SHANTY TOWN

Heliopolis

Heliopolis

SOLAR ELECTRIC (Xe) L1 ←→ GEO TUG

~ 3 km/s

~ 4 km/s

NUCLEAR THERMAL (H2) LEO ←→ L1 SHUTTLE

GEO

SPS's AND COMMSATS

LEO

NOVA-CLASS BIPROP (LO2,LH2) TO LEO

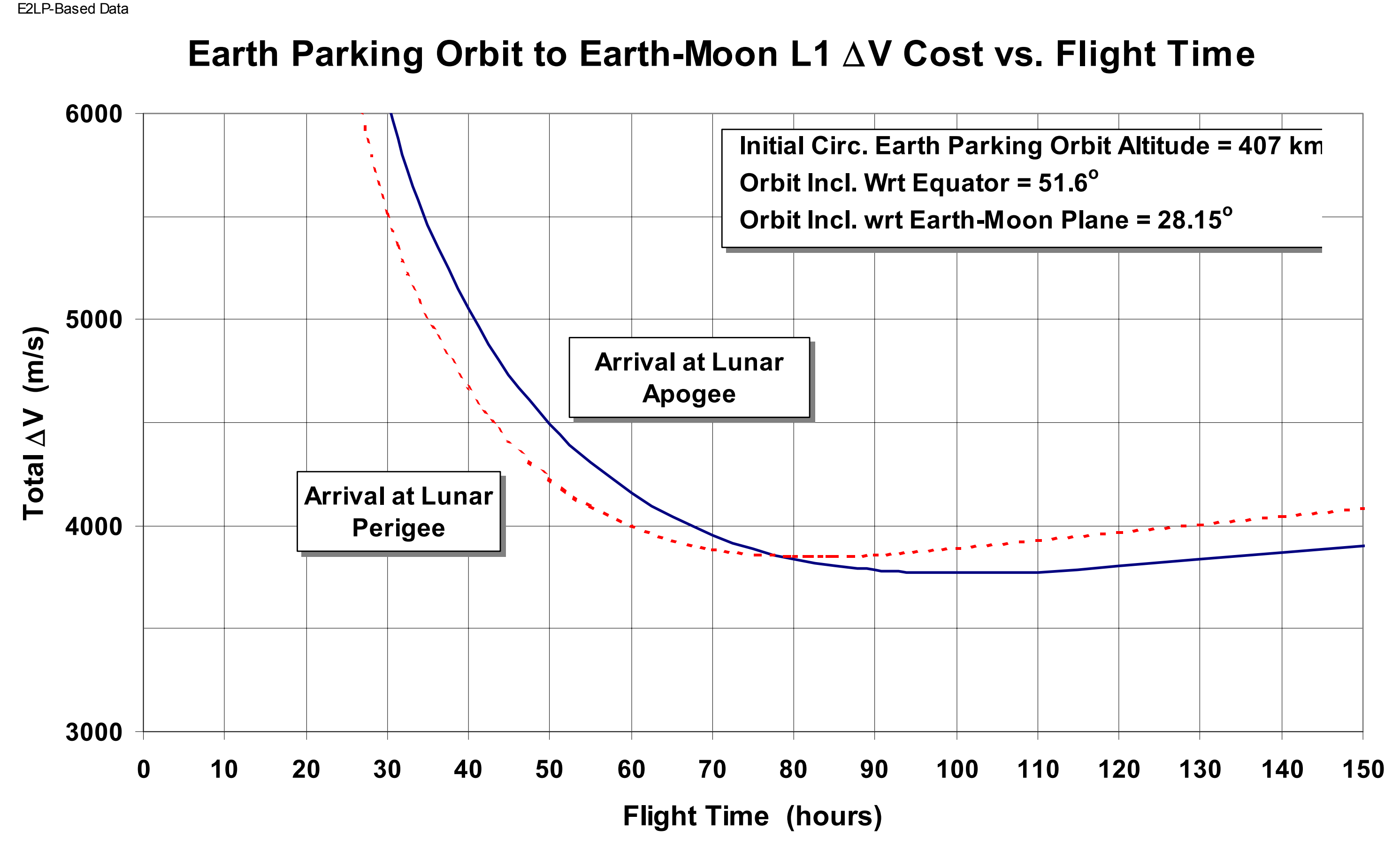
250 TONNE PAYLOAD

~ 9 km/s

EARTH

Transportation: Delta V to L1

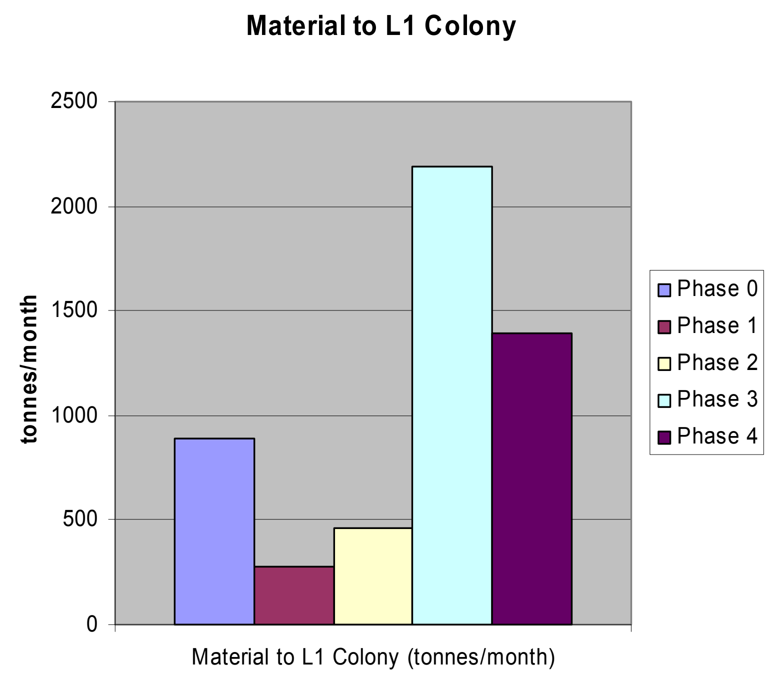
- From Low Earth Orbit
  - Impulsive propulsion

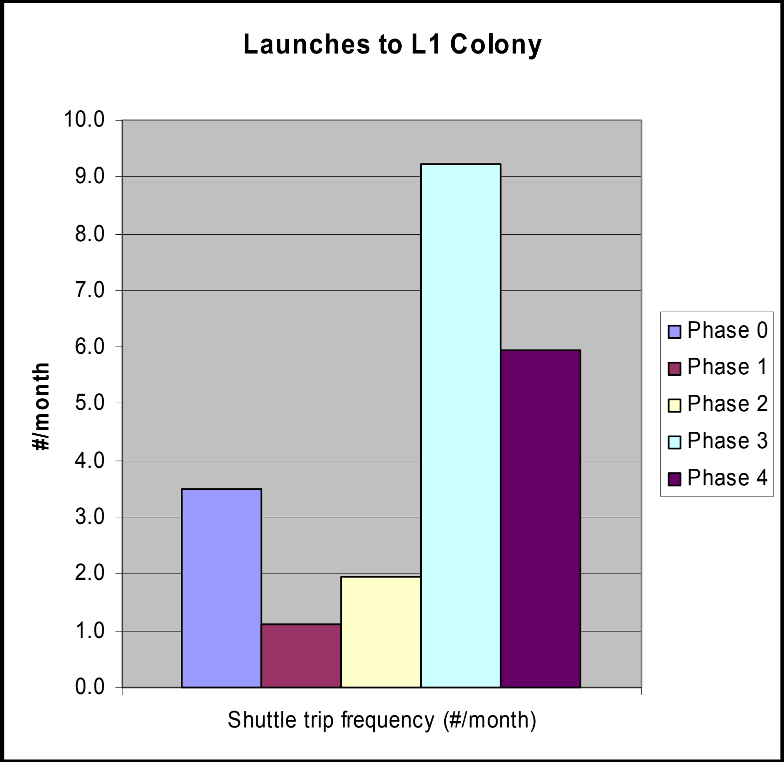


Data from Condon and Pearson [2001]

LEO/L1: Inputs

- Earth to L1 Colony
  - Material transport / trip frequency





LEO/L1: Assumptions/Outputs

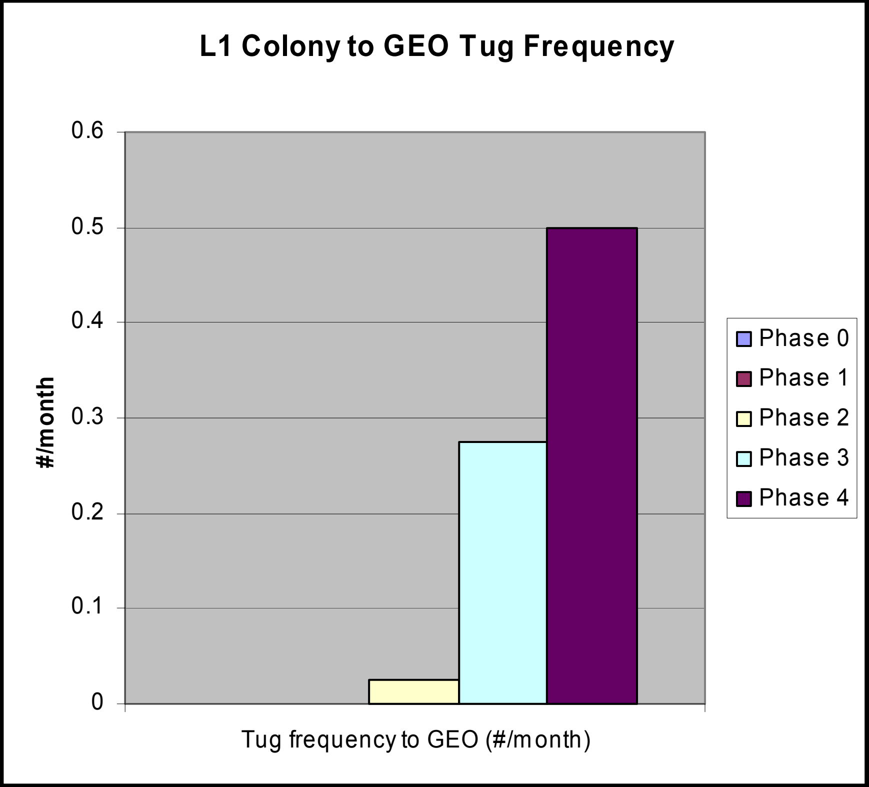
- Launch Services: Earth to LEO
  - LEO payload = **250 tonnes** (NOVA-class)
  - biprop, LO2/LH2

- LEO ⇔ L1 Colony "Shuttle"
  - Nuclear thermal, **250 tonnes** of payload to L1
  - Propellant: H2
    - Phases 0–2 : Purchased from Earth unless lunar source discovered
    - Phases 3+ : Available from retrieved asteroid

	Phases	0	1	2	3	4		Assumption Source
	Isp	1000	1000	1000	1125	1250	sec	Sercel: Technological progress
Assumptions	Factor	10%	7%	5%	4%	3%	%	Sercel: Technological progress
	Tankage Factor	25%	25%	20%	16%	12%	%	Sercel: Technological progress
	# of passengers	20	30	40	50	60	#	Ross: 10 more each phase
	One-way TOF	3	3	2.5	1.5	1	days	Ross: Faster transit with time
Outputs	Delta-V	3900	3900	4100	5300	6500	m/s	
	Mprop	98.4	95.7	96.3	106	112	tonnes	
	Mstructure	49.6	41.4	31.8	26.9	20.9	tonnes	
	Mtotal	398	387	378	383	382	tonnes	

L1/GEO: Inputs

- L1 Colony ⇔ GEO “Tug”



L1/GEO: Assumptions/Outputs

- L1 Colony ⇔ GEO “Tug”
  - Required for Phases 2 – 4
  - 45,000 tonne SPS delivered to GEO in 14 days
  - Solar Electric Propulsion
  - Propellant: Xenon, purchased from Earth-based supplier

	Phases	2	3	4		Assumption Source
Assumptions	Type	Xenon	Xenon	Xenon		Sercel/Ross: Existing technology
	Isp	3500	4000	5000	sec	Ross:Technological progress
	Round-trip TOF	14.0	14.0	14.0	days	Ross: two weeks
	Thrust per unit power	41.9	47.9	59.9	N/MW	Ross: Scaled with Isp
	Thrust per unit mass	460.0	920.0	1840.0	N/tonne	Ross: Twice each phase
	Structure Factor	0.10%	0.10%	0.10%	%	Ross
	Tankage Factor	10%	8%	5%	%	Ross:Technological progress
	Power Factor	2.50	1.00	0.50	tonnes/MW	Parker
Outputs	Delta-V	3241	3241	3241	m/s	
	Thrust	120.7	120.7	120.7	N	
	Power	2.88	2.52	2.01	MW	
	Mprop	4.25	3.72	2.98	tonnes	
	Mthrusters	0.262	0.131	0.066	tonnes	
	Msolararray	7.20	2.52	1.01	tonnes	
	Mstructure	52.2	47.7	46.2	tonnes	
	Mtotal	45064	45054	45052	tonnes	

Continuous Thrust Calculation

- **Propellant for tug**
  - Edelbaum's equation:
    $\Delta V_2 = V_0^2 + V_1^2 - 2\, V_0 V_1 \cos(\pi\, i\, /\, 2)$
  - where V_0, V_1 = circular orbital velocities, i = change in inclination in degrees
  - $\Delta V = 3.24$ km/s from L1 to GEO
  - SPS: $m_{pl} = 45{,}000$ tonnes
  - Roundtrip time: t = 14 days,
  - Thrust: $T = \Delta V * m / t = 121$ N
  - Total thruster mass = 60.7 tonnes
  - Propellant estimate: $m_p = T/(g\, I_{sp})\, t$
- **Tug: roundtrip to GEO**
  - m_p = **4,660 tonnes/trip**
  - For $I_{sp} = 3200$ s in Phase 1

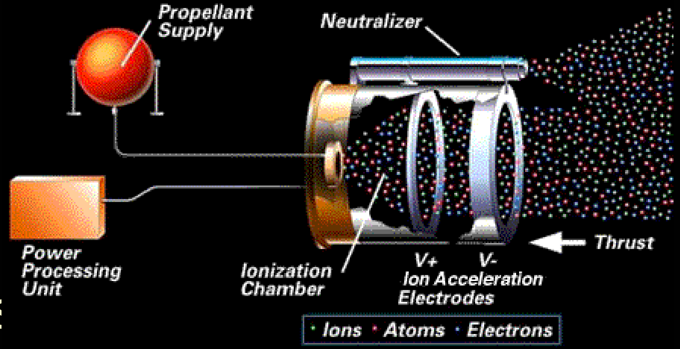
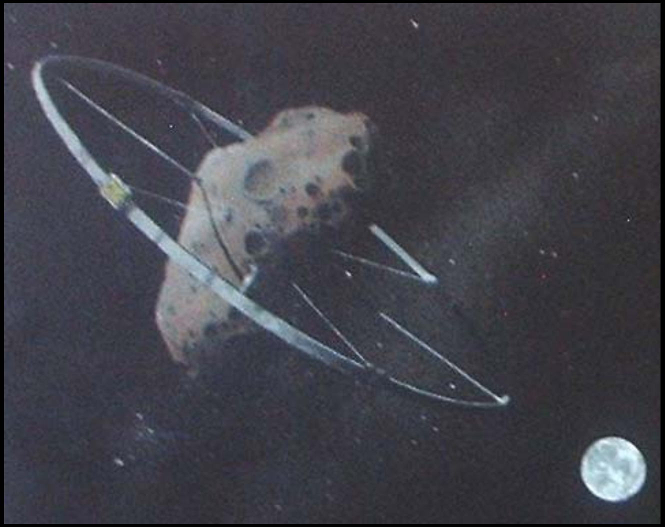


Image from Boeing website:
www.hughespace.com/factsheets/xips/xips.html

Near-Earth Asteroid Retrieval

- **Asteroid Retrieval Vehicle**
  - **Lunar derived monopropellant for propulsion out to asteroid**
    - Al_2O_3 made from lunar regolith
    - $I_{sp} = 315$ sec
    - Rocket equation:

      $$m_p = m_0 \left(1 - \exp[-\Delta V/(g\, I_{sp})]\right)$$
    - where $m_0 = m_{st} + m_{pl}$
  - **Closest asteroids (in energy)**
    - $\Delta V = 3900$ m/s
    - Asteroid retrieval vehicle sent out in Phase 2
  - **Mass driver propulsion assumed for return journey**
    - Returns in Phase 3
    - Mass Payback Ratio assumed to be 1000[1]
    - **Asteriod of mass ~ 10^7 tonnes, diameter ~ 300 m**



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[1] Lewis & Lewis [1989]

Transportation: Conclusions

- **Earth/LEO**
  - NOVA-class, 250-tonnes-to-LEO heavy lift launch vehicle is assumed

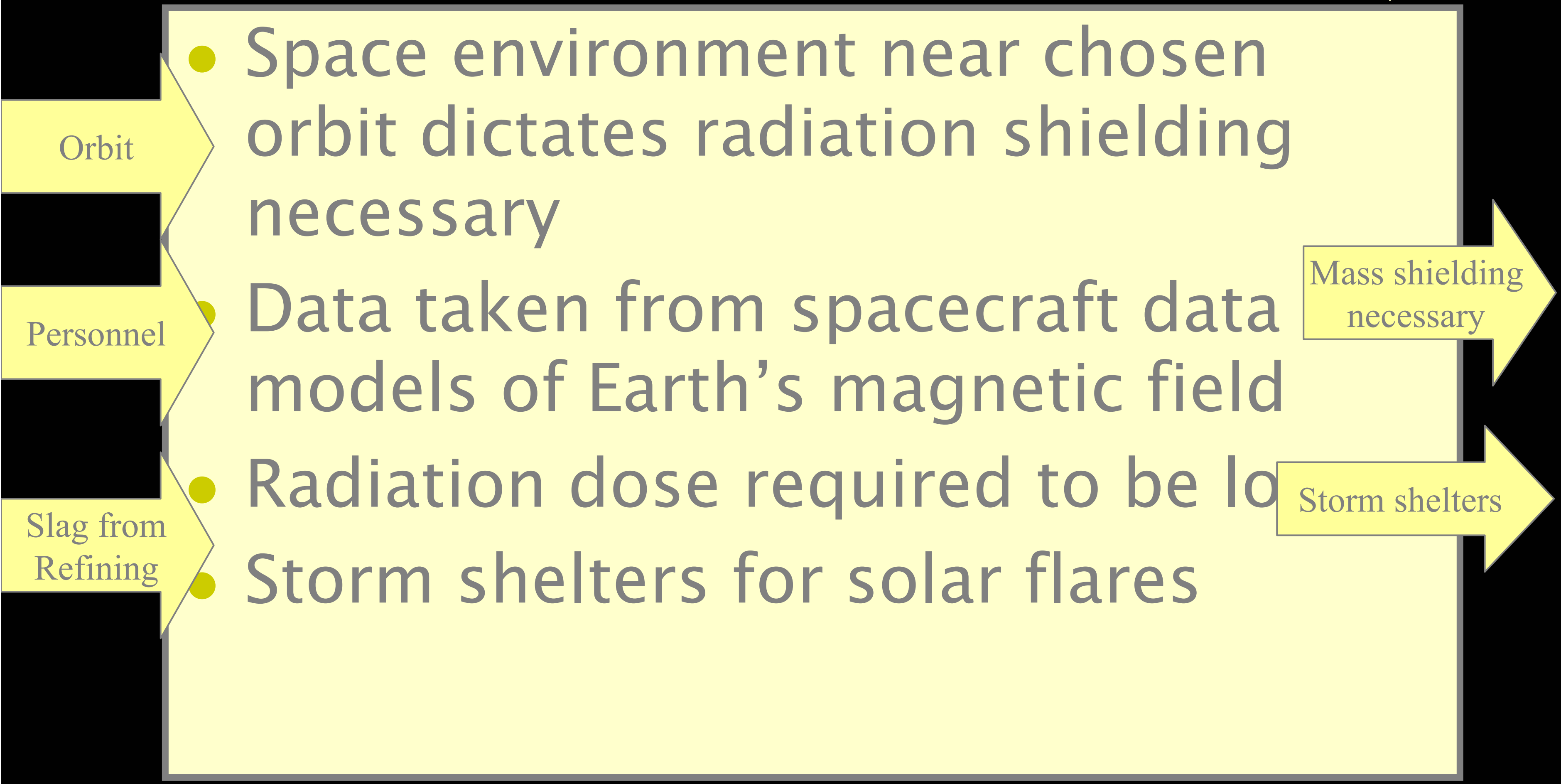
- **LEO/L1**
  - 1-3 day trip times are feasible with nuclear propulsion and H_2 propellant

- **L1/GEO**
  - Solar electric propulsion
  - Consider argon or oxygen
    - Readily available from lunar regolith

- **Asteroid Retrieval**
  - Al_2O_3 monopropellant to rendezvous
  - Mass driver assumed for return

- **Other propulsion systems to consider**
  - Beamed energy from colony to tug
  - Solar sails

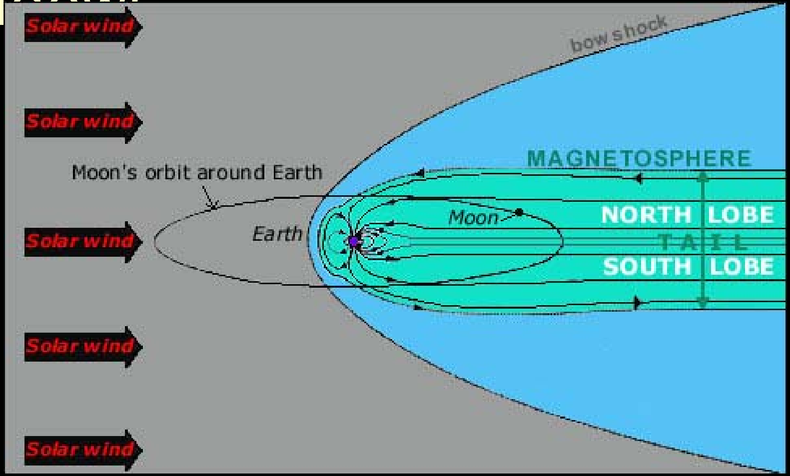
Radiation Shielding



- Space environment near chosen orbit dictates radiation shielding necessary
- Data taken from spacecraft data models of Earth’s magnetic field
- Radiation dose required to be lo
- Storm shelters for solar flares

Radiation Shielding

- **Requirement: Personnel dosage below 0.25 rem/year**
- **L1 orbit requires radiation shielding**
  - Solar cosmic particle radiation flux is uni-directional due to Earth's magnetic field, and is the most harmful[1]
  - Omni-directional shielding for galactic cosmic rays
  - Allow for windows



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[1] Thomas F. Tascione, *Introduction to the Space Environment* (2nd ed) [1994], p. 141.

Radiation Shielding

- **Little extra external shielding needed**
  - 4.3 cm of aluminum shielding necessary[1]
  - 3.8 cm layer of aluminum provided by structure
  - Use **slag** from refining, in non-rotating outer toroidal shells
  - 12 cm of slag shielding necessary[2]
    - **31,500 tonnes** of slag for Heliopolis

- **Solar flare storm shelters**
  - Need thick walls to handle large isotropic radiation flux
    - Conservative slag thickness = **3.0 m**
  - Storm shelters for **600** people each, and assume 10 m^3/person
    - Mass per storm shelter = **7,730 tonnes**
  - For 2,900 people, need **5 shelters**
  - Total storm shelter mass = **38,600 tonnes**

---

[1] Based on an aluminum thickness of 12 g/cm^2 and data from Tascione [1994]

[2] Slag assumed to have density of 1.3 g/cm^3 and same shielding ability as lunar regolith

Radiation Shielding

- **Conclusions**
  - **External Shielding**
    - Aluminum structure and slag from refining is adequate
      - Aluminum structure provides 90% of the necessary shielding
      - For a slight increase in structure thickness, slag is unnecessary
      - May simplify construction
  - **Solar Flare Storm Shelters**
    - Slag is adequate
    - Five shelters necessary at 38,600 tonnes each

---

[1] Based on an aluminum thickness of 12 g/cm^2 and data from Tascione [1994]

[2] Slag assumed to have a density of 1.3 g/cm^3 and same shielding ability as lunar regolith

Technical Study: Overview

- Design Problems/Requirements & Solutions
- Shanty Town Description
- Heliopolis Description
- System-Level Summary
- Discussion of Economic Model
- Explanation of Subsystem Models
- **Summary**

Conclusions (1 of 3)

- O'Neill was right: world market exists to begin supply of solar energy
  - World demand of 612 QBTUs[1] far exceeds world production capability of 496 QBTUs[2]
  - SPS production can begin to supply unmet demand
- Solar energy from SPS cleaner, safer than alternatives
  - No risk of toxic wastes/spills
  - No risk of explosions or meltdowns
  - No people displaced, no land made unusable

[1] US DoE
[2] International Energy Agency

Conclusions (2 of 3)

- LSMD study comparable to 1975 Stanford study
  - Differences reflect 25 years of technological advances
- However: LSMD study represents fundamentally new analysis
  - Integrated cost model demonstrates project’s economic feasibility
- Technology exists or can be designed to begin project in the next 20 years

Conclusions (3 of 3)

- Economic profit returned in 20 years
  - Positive cash flow in 15 years
  - Initial investment of $106 billion
  - Self-sufficiency and internalizing costs critical to project success
- Power requirements dominated by industrial refinery needs
- Project cost driven by food production
  - Low mass, but biomass only available from Earth
  - Personnel costs surprisingly insignificant