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IN-SPACE WATER SUPPLY CHAIN SERVICING THE U.S. MILITARY

A PRELIMINARY ESTIMATE OF FUTURE POTENTIAL U.S. MILITARY SUPPLY AND DEMAND FOR IN-SPACE WATER-BASED FUEL

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SPACE RESOURCES ROUNDTABLE - JUNE 2019

WATER SUPPLY AND DEMAND

Supply

	Moon	Near Earth Asteroids	Asteroid Belt
Pros	Close	Potential low delta-V	Enormous supply
	Diverse resources & applications	Significant supply	Diverse resources
Cons	Relatively high delta-V	Highly variable	High delta-V
	Finite supply	Significant unknowns	Far away

Demand

- Demand estimates based on current U.S. military assets in orbit
- Future trends for satellite development are unknown
- Future assets may be smaller & decentralized, but advancements could dramatically change this

CALCULATING DEMAND

DEMAND ASSUMPTIONS AND METHODOLOGY

Assumptions

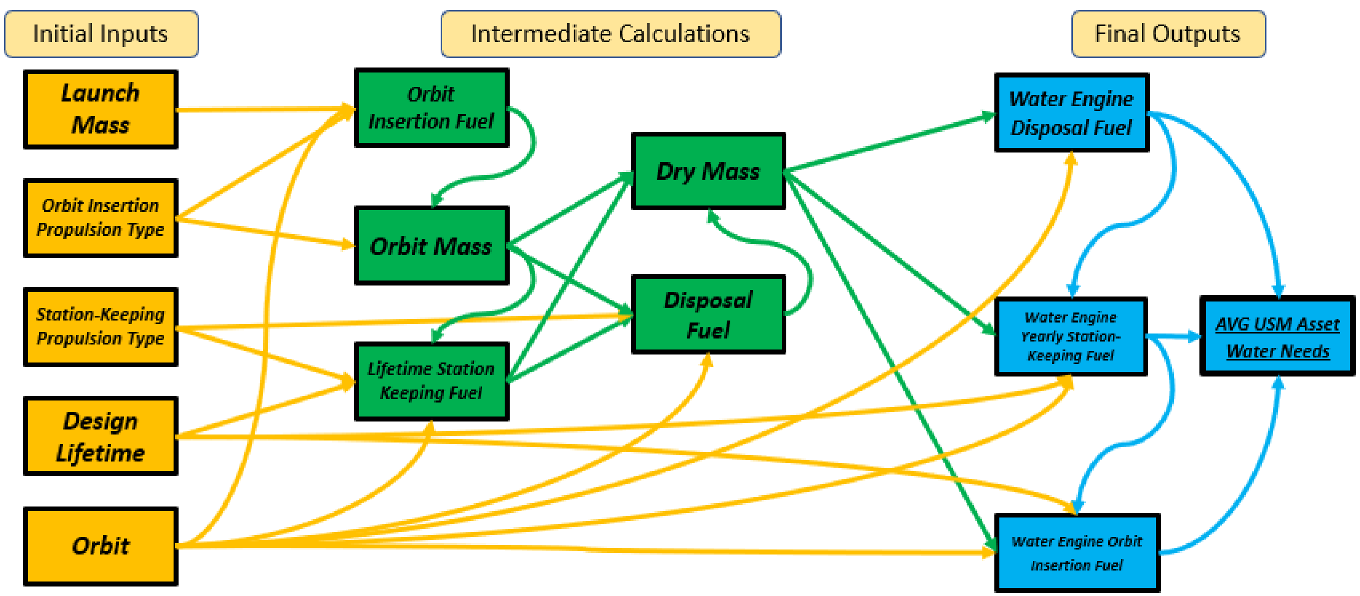
Deriving water needs:

- All fuel is replaced with water (ISP ~180)
- Fueling occurs in LEO for deployment
- Dry mass of satellites does not change
- CubeSats not considered

Future assets:

- Follow same orbital distribution
- Lifetime of 20 years
- 10X current maneuverability
- 10% share of all ISRU water

Methodology



USG ASSETS RESULTS

Based on ~130 military assets, it was estimated:

- Current demand is ~45 tons of water per year
- 333 kg of water per asset per year

A future water propelled U.S. military asset would require:

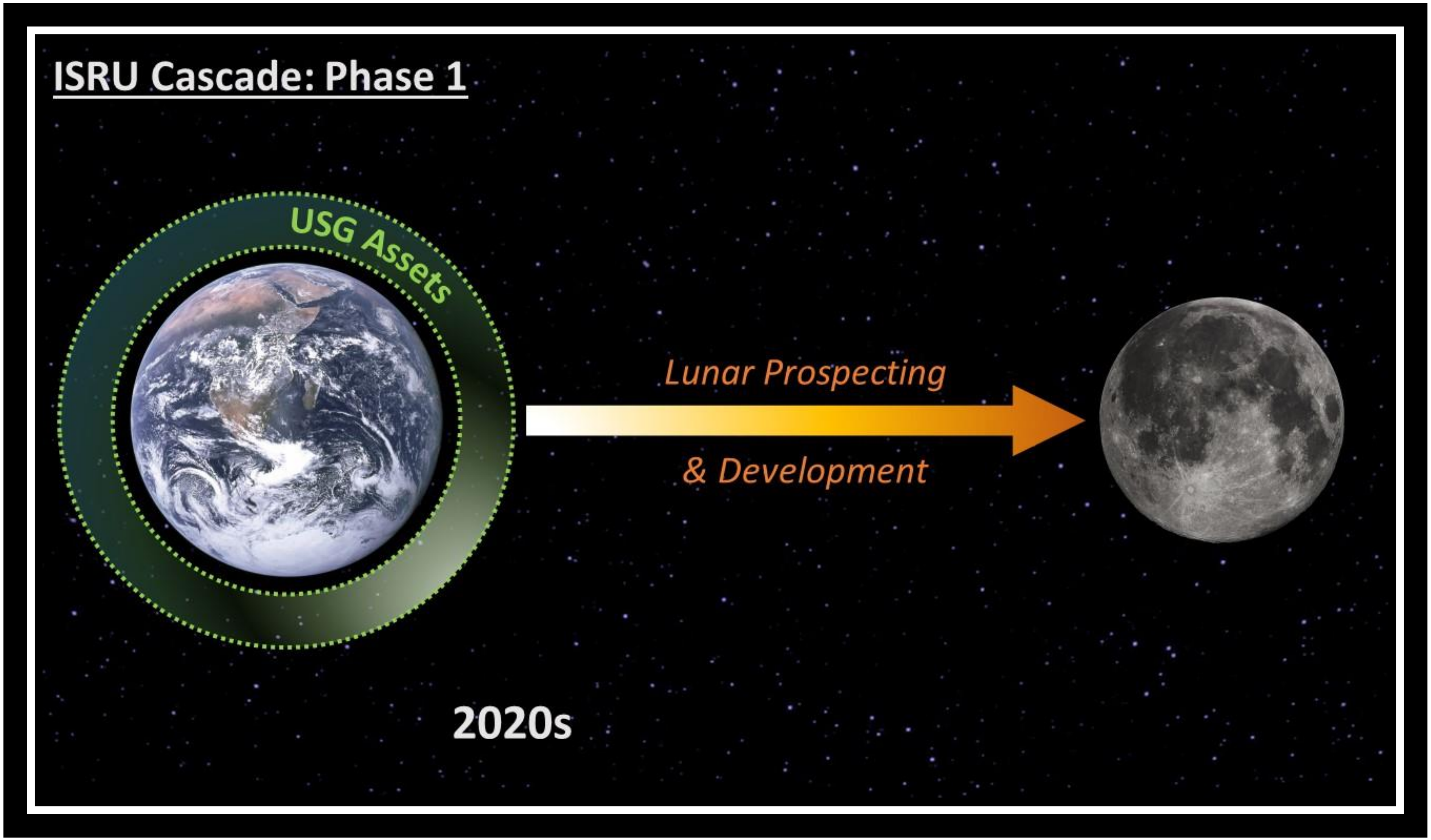
- 3,000 kg for deployment
- 130 kg for disposal
- 610 kg per year for station keeping

Supply chain demand:

- ~40% Fuel for LEO
- ~20% Fuel for MEO
- ~40% Fuel for GEO

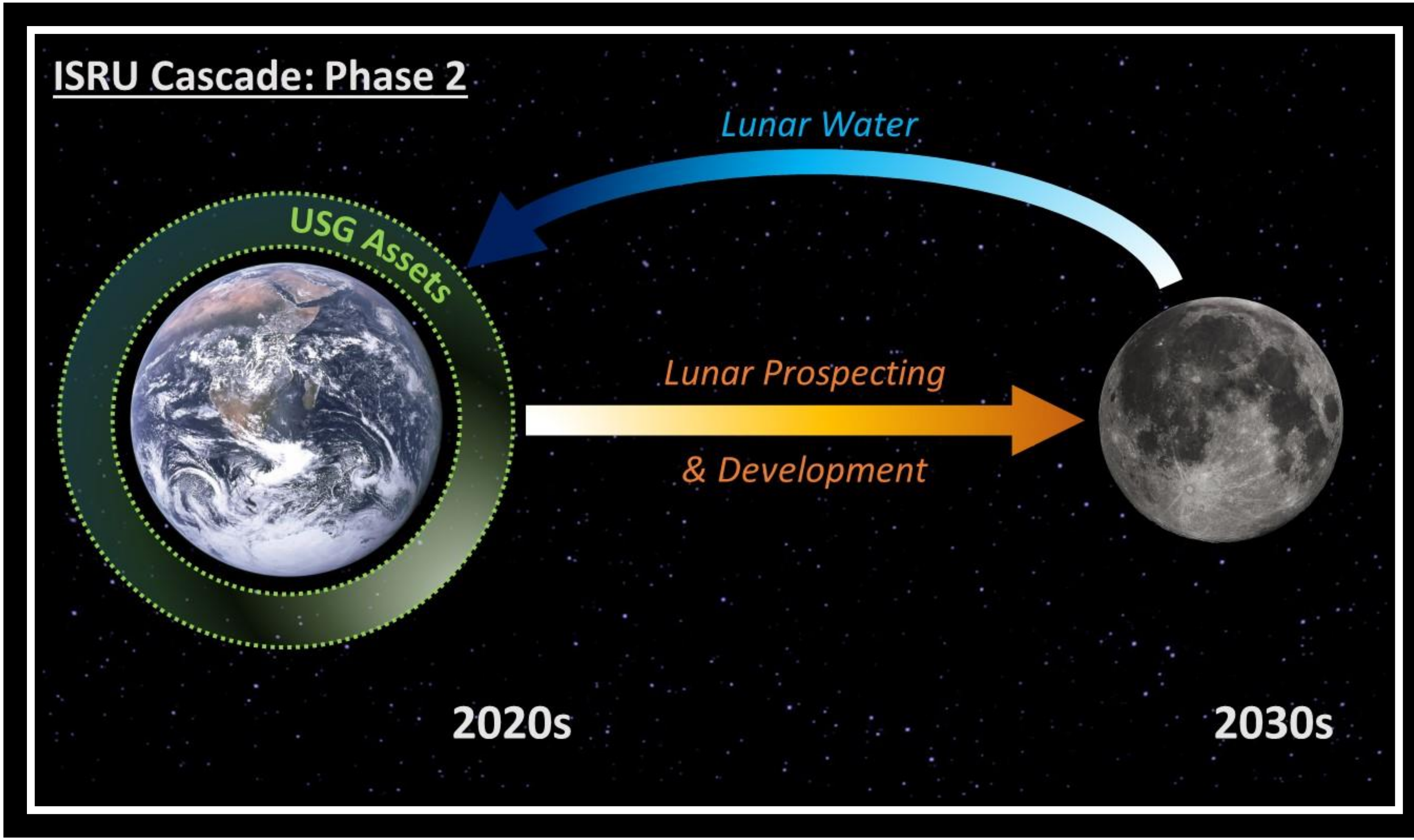
Transportation to destination orbit needs 50% for LH2/LOX and 10% for ion/plasma

SUPPLY CHAIN ROAD MAP



CALCULATING SUPPLY 1: THE MOON

SUPPLY CHAIN ROAD MAP



LUNAR ASSUMPTIONS AND METHODS

Assumptions

- 1.2×10^{12} kg of water located at the Lunar Poles
- U.S. Military has 10% share of total
- About 2/3 of the dry mass of Lunar escape vehicles is payload
- LH2/LOX fuel for Lunar escape
- Ion/plasma propulsion used for final fuel delivery

Methods

- 10% multiplier for 10% share of total water
- ~50% multiplier for water loses due to Lunar escape
- ~90% multiplier for water loses due to destination orbit insertion

Leaving 5.2×10^{10} kg for military assets

LUNAR RESULTS

Accessible with conventional technology

Relatively high magnitudes of water

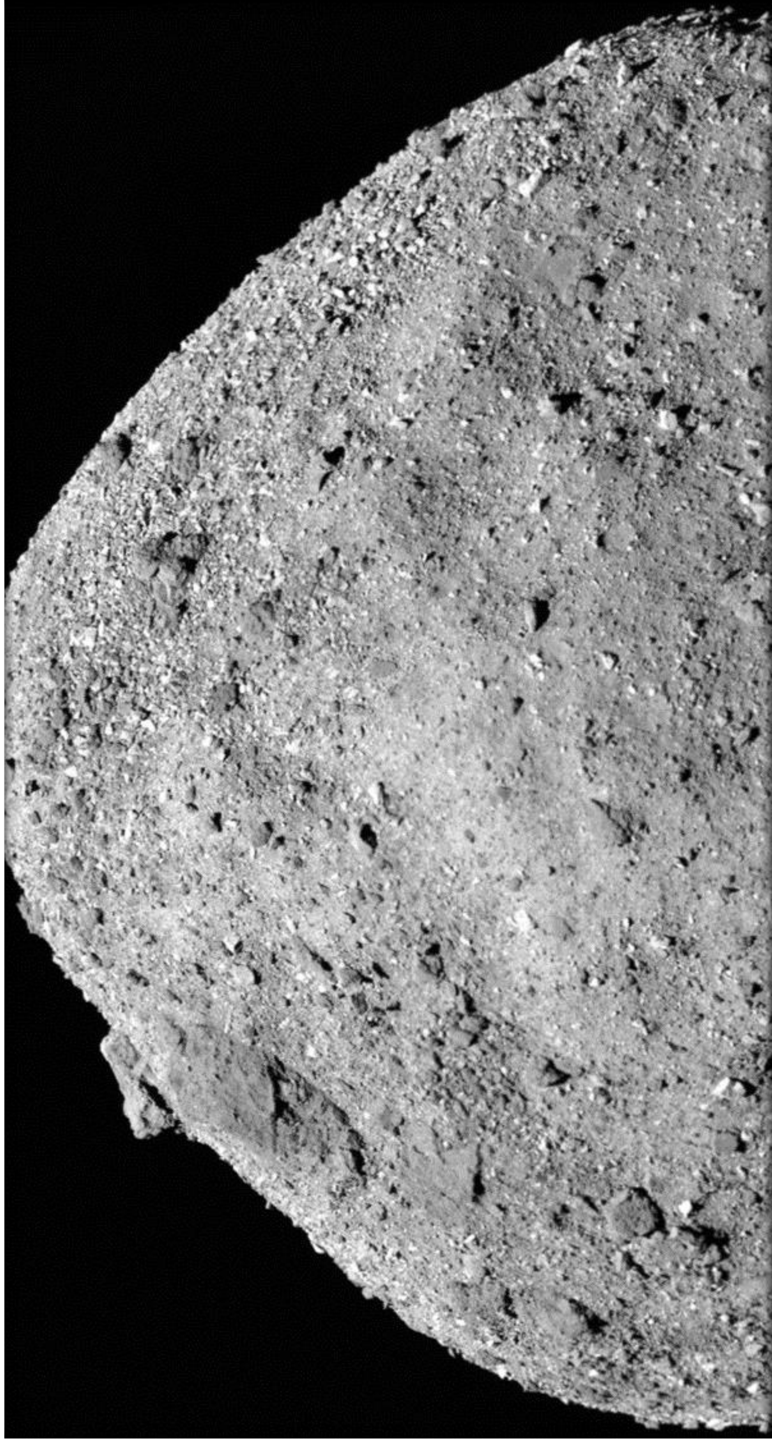
Important stepping stone to future supply chains

Easier to disrupt

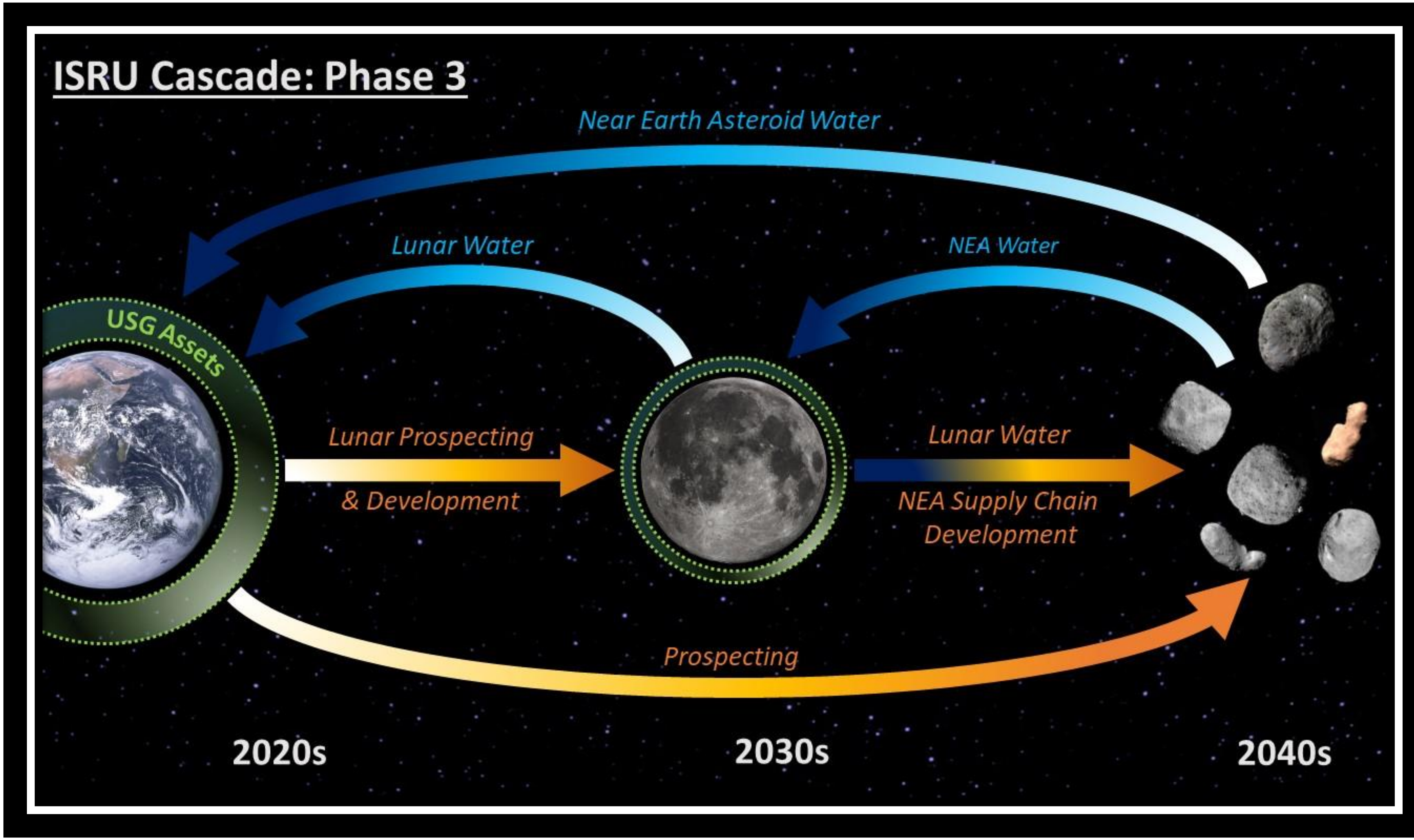
More Competition

Independent Lunar Supply Chain	
Source Water Mass	1.2 x 10^{12} kg
Delivered Water Mass	5.2 x 10^{10} kg
Theoretical Number of Deployable Assets	**~3.4 Million Assets**
Time Until Depletion	**~510 years**

CALCULATING SUPPLY 2: NEAR EARTH ASTEROIDS



SUPPLY CHAIN ROAD MAP



NEAR TERM NEA ASSUMPTIONS AND METHODS

Assumptions

- Only 5-30m asteroids are minable
- C-types make up 20% of NEAs
- Even distribution of asteroid size and type
- U.S. Military has a 10% share
- Solar baking method is scalable
- Ratio of asteroid to spacecraft is 60
- Min of 50% of water reserved for return
- 75% of the water is mined out and the remainder of the asteroid is ditched
- Fuel to despin asteroids is negligible
- LH2/LOX is used for outbound
- Derived LH2/LOX fuel for Earth return
- Ion/plasma propulsion is used for fuel delivery

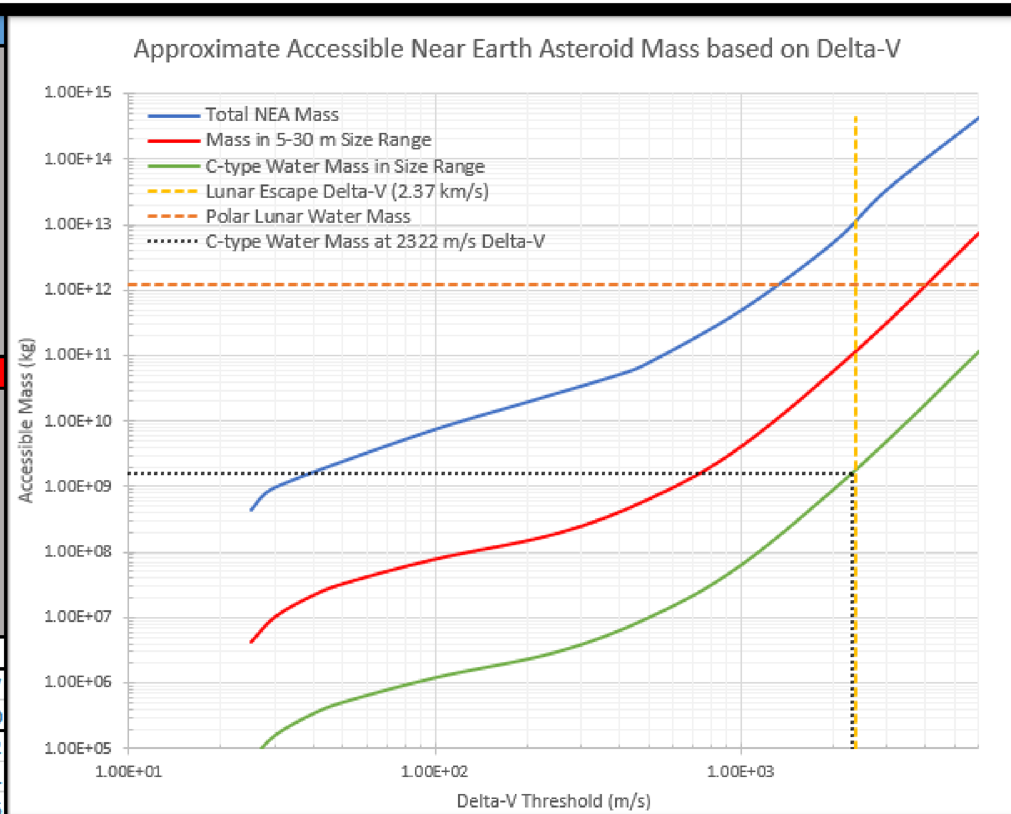
Methods

- Use assumptions to find delta-V max
- Use delta-V in broken plane delta-V function to estimate mass in range
- Adjust based on ratio in size range
- 20% multiplier for C-types
- Density adjustment multiplier
- 10% multiplier for percent water
- 75% multiplier for water taken
- 50% multiplier for water saved
- Subtract water inbound for net
- Adjust using Reiman sums to account for greater recovery at all lower delta-Vs
- 10% share of total water
- ~90% multiplier for water loses

Leaving 5.3×10^7 kg for Military Assets

NEAR TERM NEA MODEL

Asteroid Retrieval via Bagging and Water Thruster		
Initial Inputs		
Minimum Asteroid Diameter (m):	5	
Maximum Asteroid Diameter (m):	30	
Asteroid to Dry Spacecraft Mass Ratio:	60	
% of Asteroid's Water Saved for Recovery:	50	
Specific Impulse to Asteroid (s):	450	
Specific Impulse back from Asteroid (s):	450	
Ditch Rest of Asteroid? (1=No, 2=Yes):	2	
% of Asteroid H2O Baked out for Recovery:	75	
Outputs		
Max Delta-V (m/s):	2,321.73	
Water Mass from C-types in Range (kg):	1.61E+09	
Water Mass Recoverable w/ Settings (kg):	6.93E+08	
Percentage of Water Mass Recoverable:	43.01	
Net Water Mass Gained w/ Settings (kg):	5.83E+08	
Overall Net Water Return Ratio	5.28	
Number of C-type Asteroids in Range:	15,262	
Test Cases at Max Delta-V:	**5 m (min)**	**30 m (max)**
Asteroid Mass (kg):	1.31E+05	2.83E+07
Spacecraft Mass (kg):	2,181.66	471,238.90
Recovered Water Mass (kg):	4,908.74	1,060,287.52
Initial Water Needed (kg):	1,510.38	326,242.31
Water Return Ratio:	3.25	3.25



NEAR TERM NEA RESULTS

Comparatively low water mass

Extremely efficient for early ISRU cascade all within Lunar delta-V

Water return ratio here is 5 times the investment

Provides value as a redundant supply chain

Hard to disrupt

Independent Near Term NEA Supply Chain	
Source Water Mass	1.6 x 10^9 kg
Delivered Water Mass	5.3 x 10^7 kg
Theoretical Number of Deployable Assets	**~3400 Assets**
Time Until Depletion	**~170 years**

LONG TERM NEA ASSUMPTIONS AND METHODS

Assumptions

- All NEAs accessible with minimal in-bound loss
- C-types make up 40% of NEAs
- Even distribution of asteroid size and type across delta-V ranges
- All C-type asteroids can be mined
- 100% of the water is mined and the remainder of the asteroid is ditched
- Fuel to despin asteroids is negligible
- U.S. Military has 10% share of water
- Derived LH2/LOX fuel for Earth return
- Ion/plasma propulsion used for final fuel delivery

Methods

- 20% multiplier for C-types
- Density adjustment multiplier
- 10% multiplier for percent Water
- 75% multiplier for water taken
- ~16% multiplier for loses due to Earth return
- 10% multiplier for military share
- ~90% multiplier for water loses due to destination orbit insertion

Leaving 9.8 x 10^{12} kg for Military Assets

LONG TERM NEA RESULTS

Tremendous resources available in the NEA population

Much of it is currently inaccessible

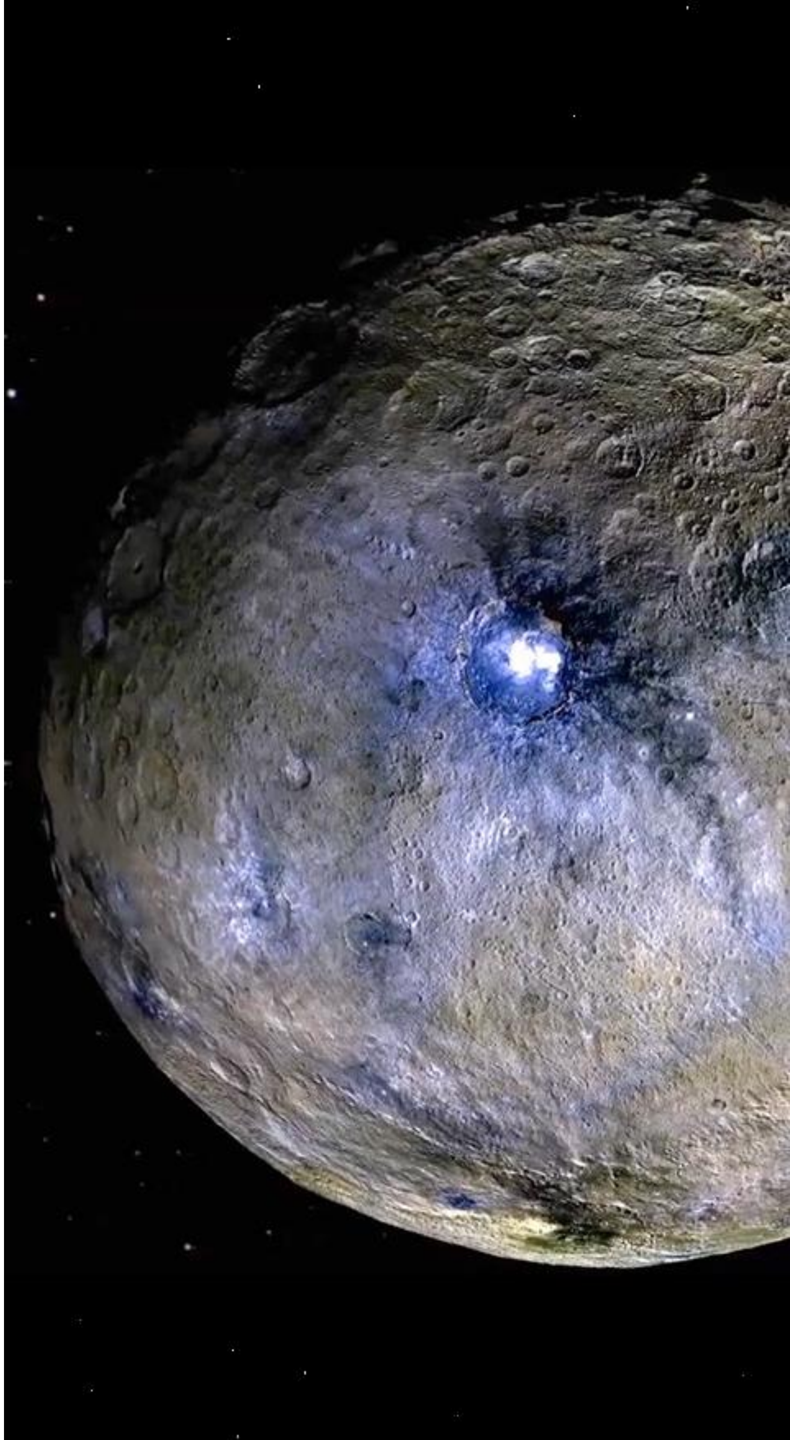
Requires significant R&D but it's worthwhile

Hard to disrupt

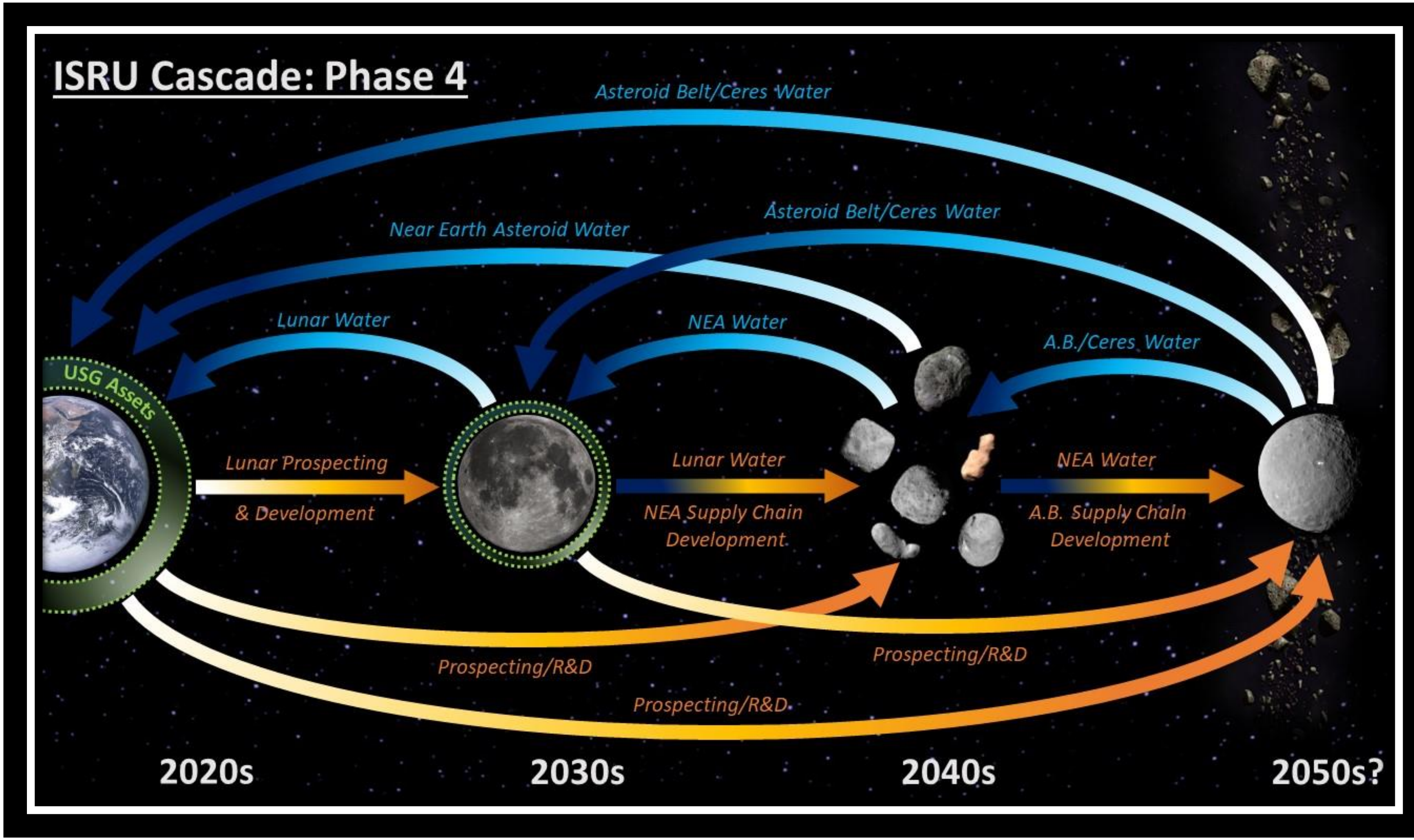
Independent Long Term NEA Supply Chain	
Source Water Mass	6.7×10^{14} kg
Delivered Water Mass	9.8×10^{12} kg
Theoretical Number of Deployable Assets	**1 Million Assets***
Time Until Depletion	**12,800 years***

**Capped at one million with demand becoming linear thereafter, as # of assets was far too great to be realistic*

CALCULATING SUPPLY 3: THE ASTEROID BELT



SUPPLY CHAIN ROAD MAP



ASTEROID BELT ASSUMPTIONS AND METHODS

Assumptions

- Asteroid belt mass is $3x10^{21}$ kg
- C-type make up 40% of the population
- C-types are 15% water by mass
- Asteroid intercept requires average delta-V of 8000 km/s
- Fuel losses due to asteroid escape are negligible
- Derived LH2/LOX fuel for Earth return
- About 2/3 of the dry mass of miner is payload
- U.S. Military has 10% share
- Ion/plasma propulsion is used for final fuel delivery

Methods

- 40% multiplier for percent C-types
- 15% multiplier for percent water
- ~13% multiplier loses due to Earth return
- ~90% multiplier for water loses due to destination orbit insertion
- 10% multiplier for the 10% share of total water

Leaving 2.1 x 10^{18} kg for Military Assets

ASTEROID BELT RESULTS

Provides inexhaustible resources

Much of this water is centralized to Ceres

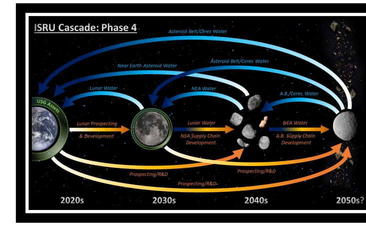
Could support planned Moon-like manufacturing

Ceres will likely be an important strategic & economic hot spot for humanity

Independent Asteroid Belt Supply Chain	
Source Water Mass	1.8×10^{20} kg
Delivered Water Mass	2.1×10^{18} kg
Theoretical Number of Deployable Assets	**1 Million***
Time Until Depletion	**2.8 Billion Years***

**Capped at one million with demand becoming linear thereafter, as # of assets was far too great to be realistic*

ALL INDEPENDENT SUPPLY CHAIN OUTCOMES



Given a 10% share of the total resources and estimated requirements for resource return, based on the average military asset with 10X maneuverability and 2% exponential growth, each supply chain could independently support:

	Lunar Supply Chain	Near Term NEA Supply Chain	Long Term NEA Supply Chain	Asteroid Belt Supply Chain
Source Water Mass	1.2×10^{12} kg	1.6×10^{9} kg	6.7×10^{14} kg	1.8×10^{20} kg
Delivered Water Mass	5.2×10^{10} kg	5.3×10^{7} kg	9.8×10^{12} kg	2.1×10^{18} kg
Theoretical Number of Deployable Assets	3.4 Million	3,400	1 Million*	1 Million*
Time until Depletion	510 Years	170 Years	12,800 Years*	Unlimited*

Note: **Capped at 1 million w/ linear demand after for asset replacement, as the exponential # of assets was unrealistic*