Xenon Acquisition Strategies for High-Power Electric Propulsion NASA Missions

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Introduction

- Solar Electric Propulsion can provide significant benefits for range of applications via high fuel-efficiency:
  - GeoComm Sats – Increase lifetime (station-keeping), increase payload (higher-Isp orbit insertion and orbit raising), dual-launch
  - Science – Enable and enhance certain mission applications (higher delivered payload and launch vehicle step-down)
 - Exploration – Reduce number of heavy launches required thereby reducing cost/complexity
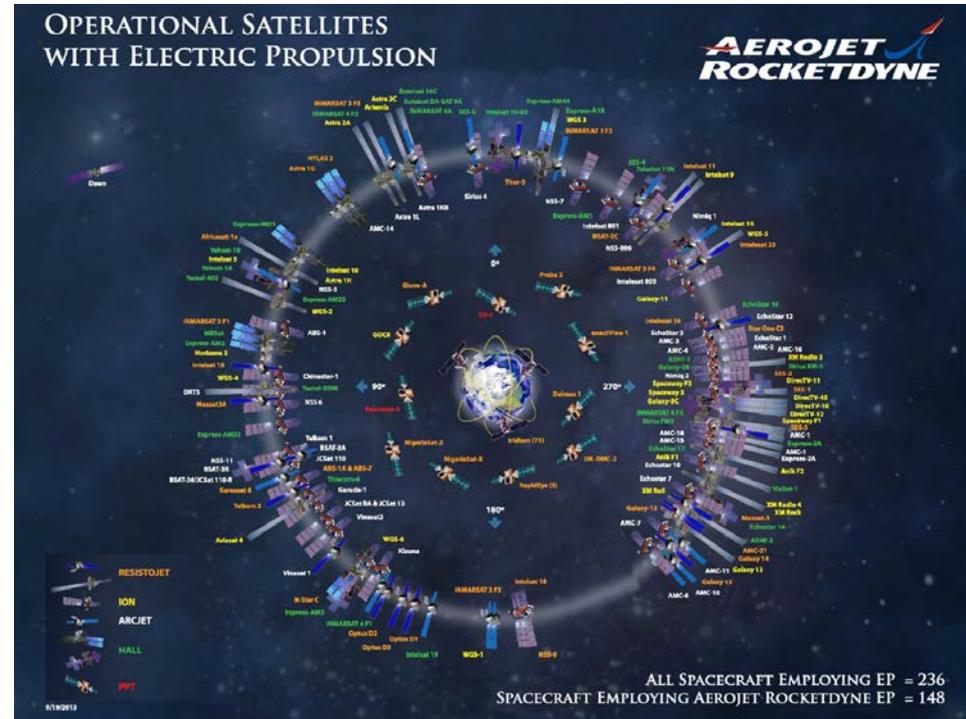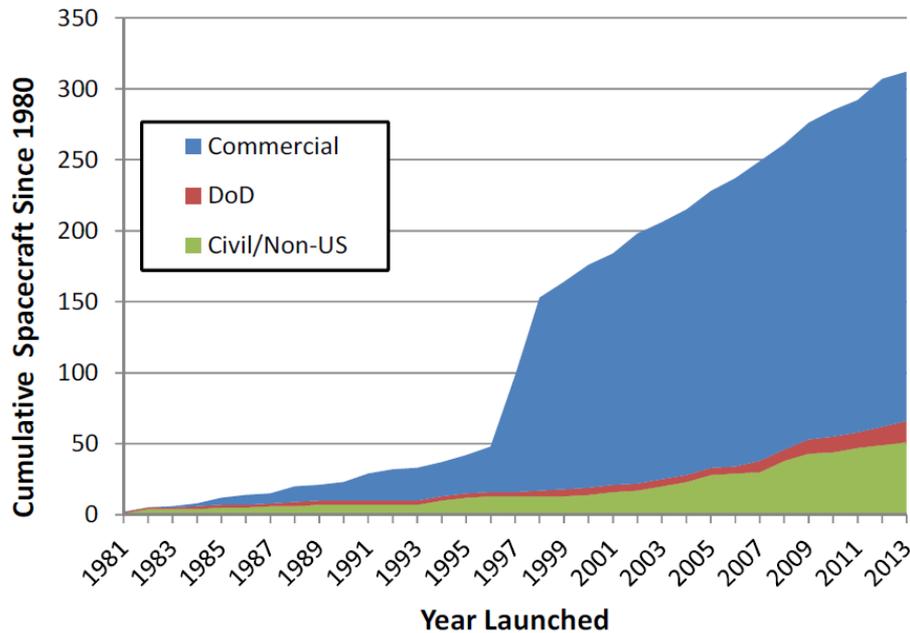
Credit: Hoskins, et. al., IEPC-2013-439

# Introduction

- NASA is developing the requisite technologies for a 50kW-Class Solar Electric Propulsion Demonstration to enable SEP missions and applications at higher power levels
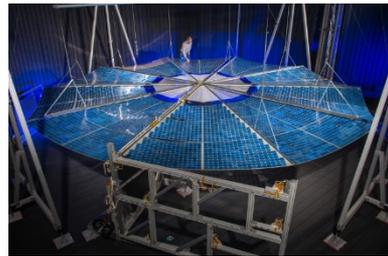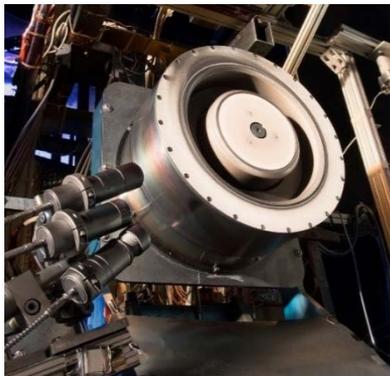
25-kW Solar Array Structures: MegaFlex (left) and ROSA (right).

12.5kW HERMES TDU-1

TDU-1 (Inside)
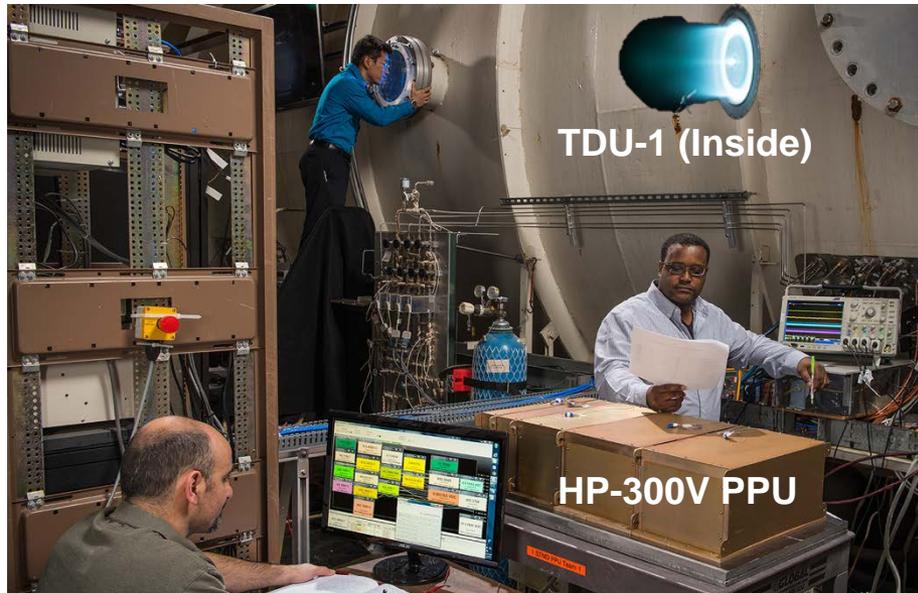
HP-300V PPU

HP-300V PPU and HERMeS TDU-1 Integration Test
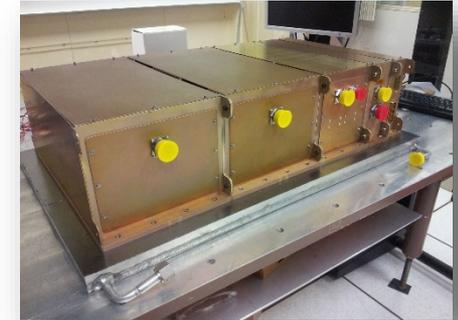
HP-300V Brassboard PPU

HP-120/800V Brassboard PPU
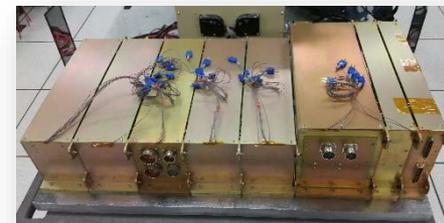
Notional Mission Concepts

- High-power SEP can be enabling for both near-term and future exploration architectures and science missions
- NASA is maturing mission design for a 50kW-Class SEP Demonstration
  - Most mature concept is the Asteroid Redirect Mission

3. Asteroid rendezvous, characterization

4. Asteroid Extraction

Large asteroid's orbit

2. SEP low thrust cruise to asteroid

5. SEP redirect to lunar orbit

Lunar orbit

7. Orion Rendezvous & crew operations

1. Launch via LGA or direct with SLS or other heavy launcher

6. Lunar gravity capture & SEP transfer to DRO
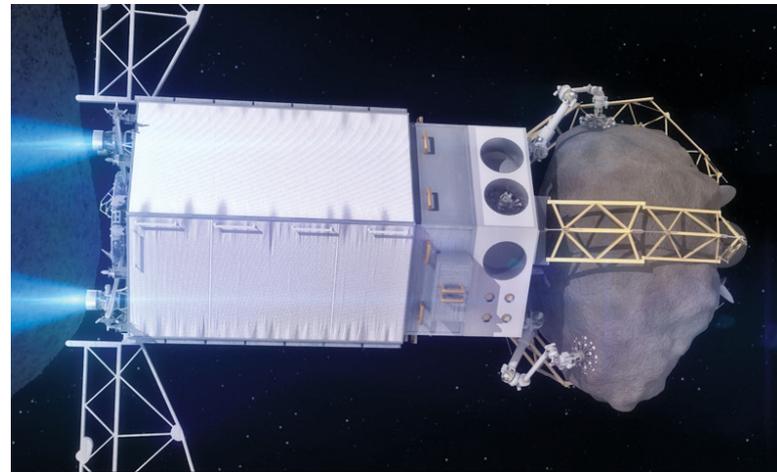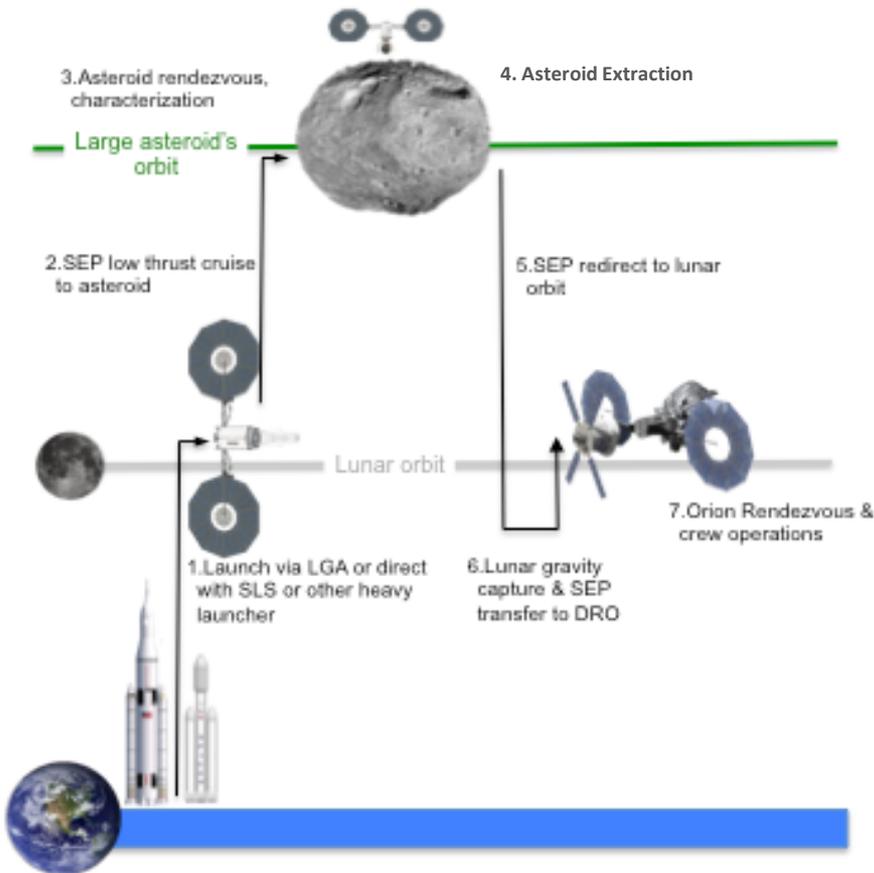
Notional Asteroid Redirect Vehicle
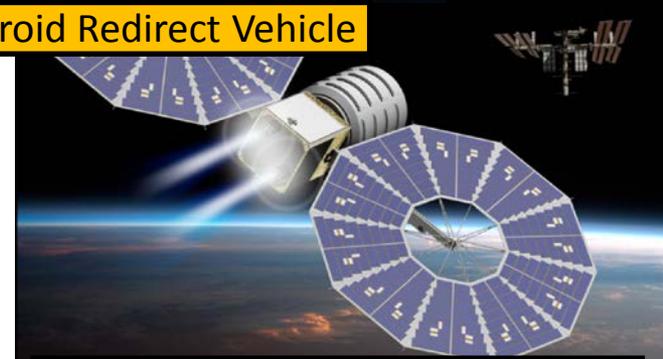
30kW-Class SEP TDM: L2 Logistics

Notional Stepping-Stone Mission Concepts

Block 1

50-kW Solar Array
40-kW EP System
10-t Xenon Capacity

Block 1a

190-kW Solar Array
150-kW EP System
16-t Xenon Capacity
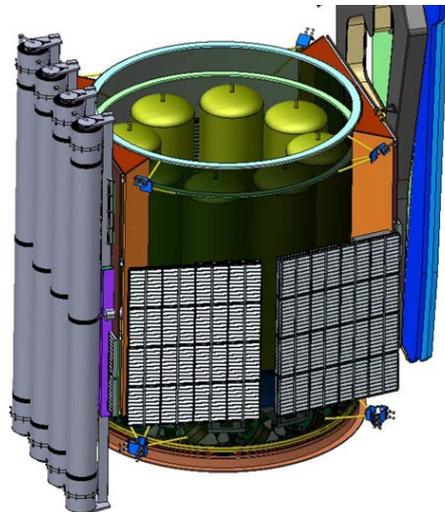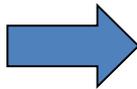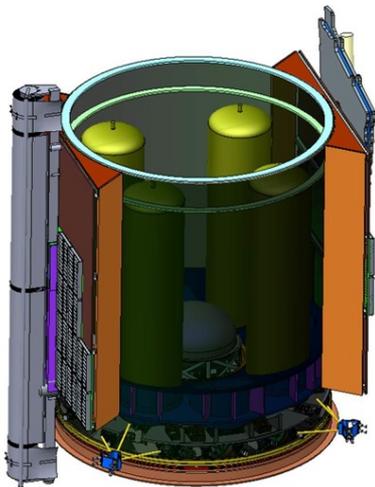
Evolvable Stepping-Stone Approach

50 kilowatt "Block 1" — 12-m dia — 4.2 m x 24 m

100 kilowatt "Block 1a" — 15-m dia — 2 each - 4.2 m x 24 m

300 kilowatt "Block 2" — 25-m dia — 8 each - 4.5 m x 17 m

MegaFlex Implementations

ROSA/Mega-ROSA Implementations
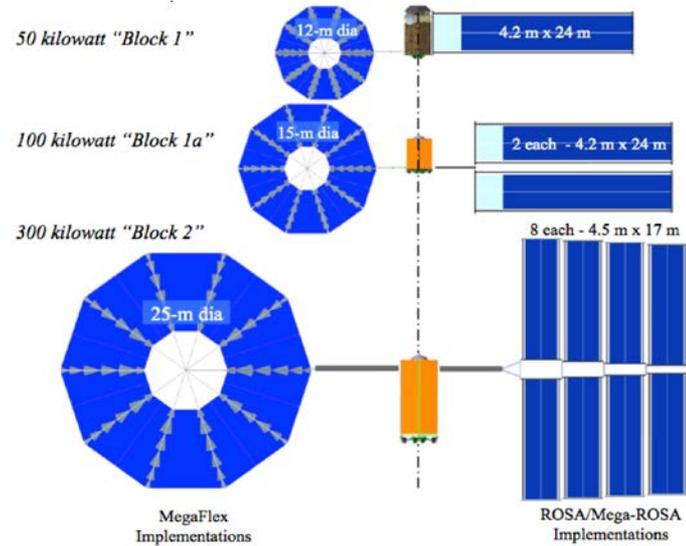
Vehicle	Xenon Load
Block 1: ARRM	≤10,000kg
Block 1a	16,000 kg
Block 2	22,000 kg

Composition of Atmospheric Air (Volume %)

N_2	78.06
O_2	20.95
Ar	0.93
CO_2	0.033
Ne	0.0018
He	0.000524
CH_4	0.0002
Kr	0.00011
H_2	0.00005
N_2O	0.00005
Xe	**0.0000087**
O_3	0.000007
H_2O	1.57 (@ 50% RH & 25°C)

Estimated 2×10^{12} kg of xenon in Earth's atmosphere

20 tons of xenon per year for in-space propulsion for next 1 million years without running out!

Xenon Production

Gases are obtained through air separation.

Linde ASU Kazincbarcika, Hungary

Xenon Production

Process Flow

LOX incl.

2000 ppm

Kr/Xe

Large Air Separation Unit (ASU)

with rare gases column

Air intake > 150,000 m³/h or

oxygen capacity > 30,000 m3/h

Kr/Xe Enrichment

99%

Kr/Xe

Separation

Pure

Kr / Xe

| 1st enrichment | 2nd enrichment | Separation |
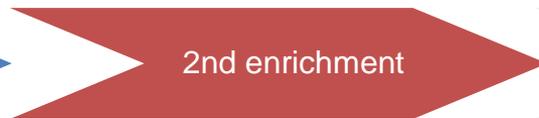
# Xenon Production

- Xenon (and krypton) are produced as co-/byproducts of cryogenic oxygen and nitrogen production.

- Air separation plants (ASUs) are designed to produce oxygen, nitrogen or both. Some larger plants have additional equipment to collect argon, neon, krypton, xenon and even helium. The major operating cost is for the electricity to chill the gases.

- It is not economical to operate a plant to collect just neon, krypton or xenon.

- Collection of krypton and xenon is only economical at very large ASUs and the collected crude gas requires further purification. Xenon producing plants typically produce 2000+ tons per day of oxygen.

- ASUs are often built near major oxygen or nitrogen users to minimize transportation costs.

- Pressure swing adsorption & membrane gas plants are not used to produce rare gases. These technologies can produce lower purity gaseous oxygen and nitrogen at a lower cost than the cryogenic process, but do not produce rare gases.

Xenon Storage

- Xenon can easily be stored and transported

- Tube trailers can transport about 10 tons of xenon at a time. They can be used to store larger quantities.

- Xenon storage assumed at supplier location not a cost driver

  - NASA estimates on storage cost are less than 3% of xenon contract total cost

Xenon Availability and Pricing Factors

- capacity of xenon collection equipment at ASUs

- ASU operating rates which are affected by the demand for
  - steel and
  - petrochemicals

- xenon demand for
  - lighting,
  - detectors,
  - plasma displays,
  - lasers,
  - dark mater research,
  - anesthesia, and
  - electric propulsion

- krypton demand

Worldwide Xenon Production Trends
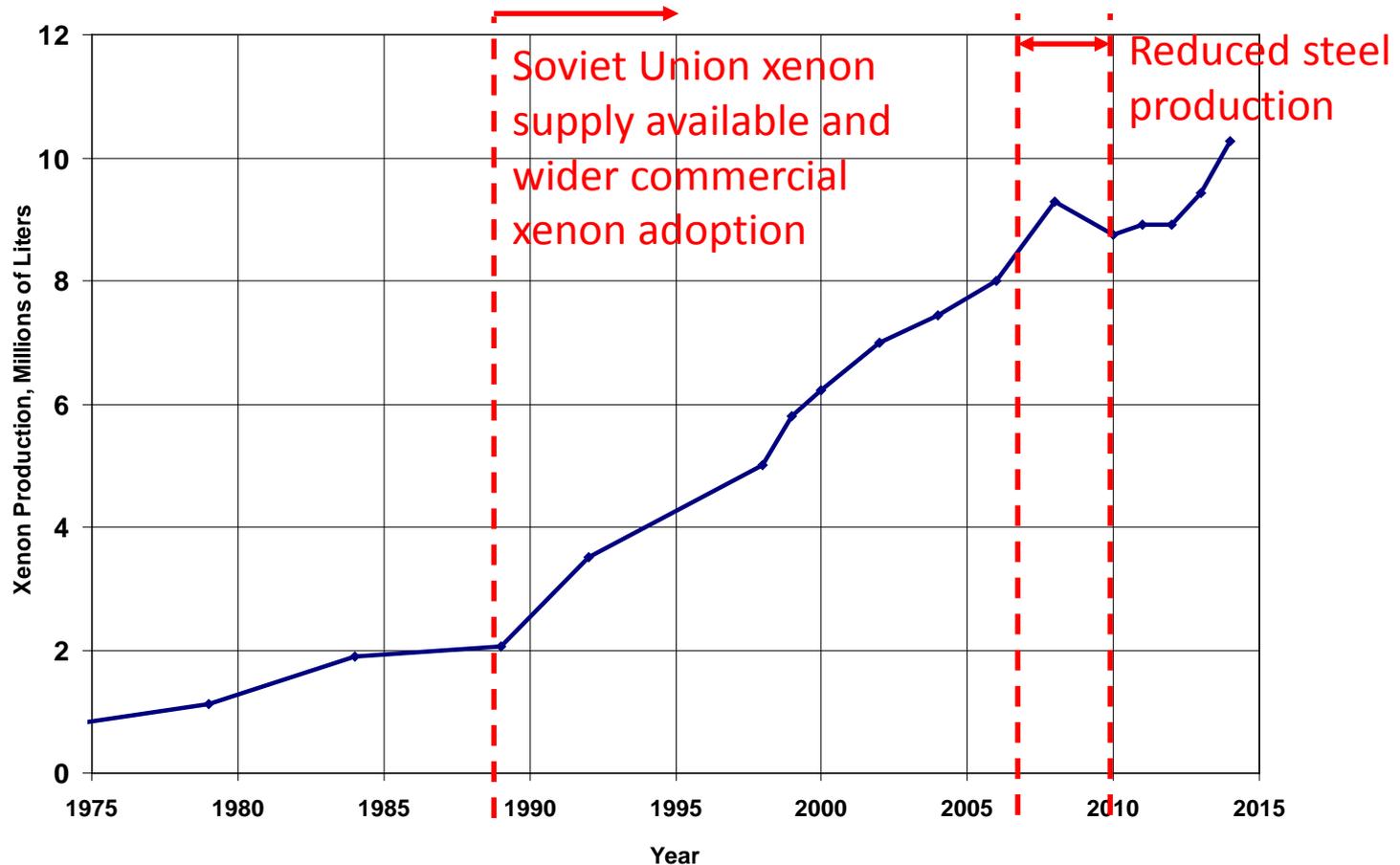
- **Global annual production estimated at 53,000 kg**
  - Electric propulsion represents 10% of the xenon market over the past 20 years
- Supply of xenon increased 10-fold over last 40 years
  - Xenon moved from specialty product to commodity

Xenon Market Price Trends
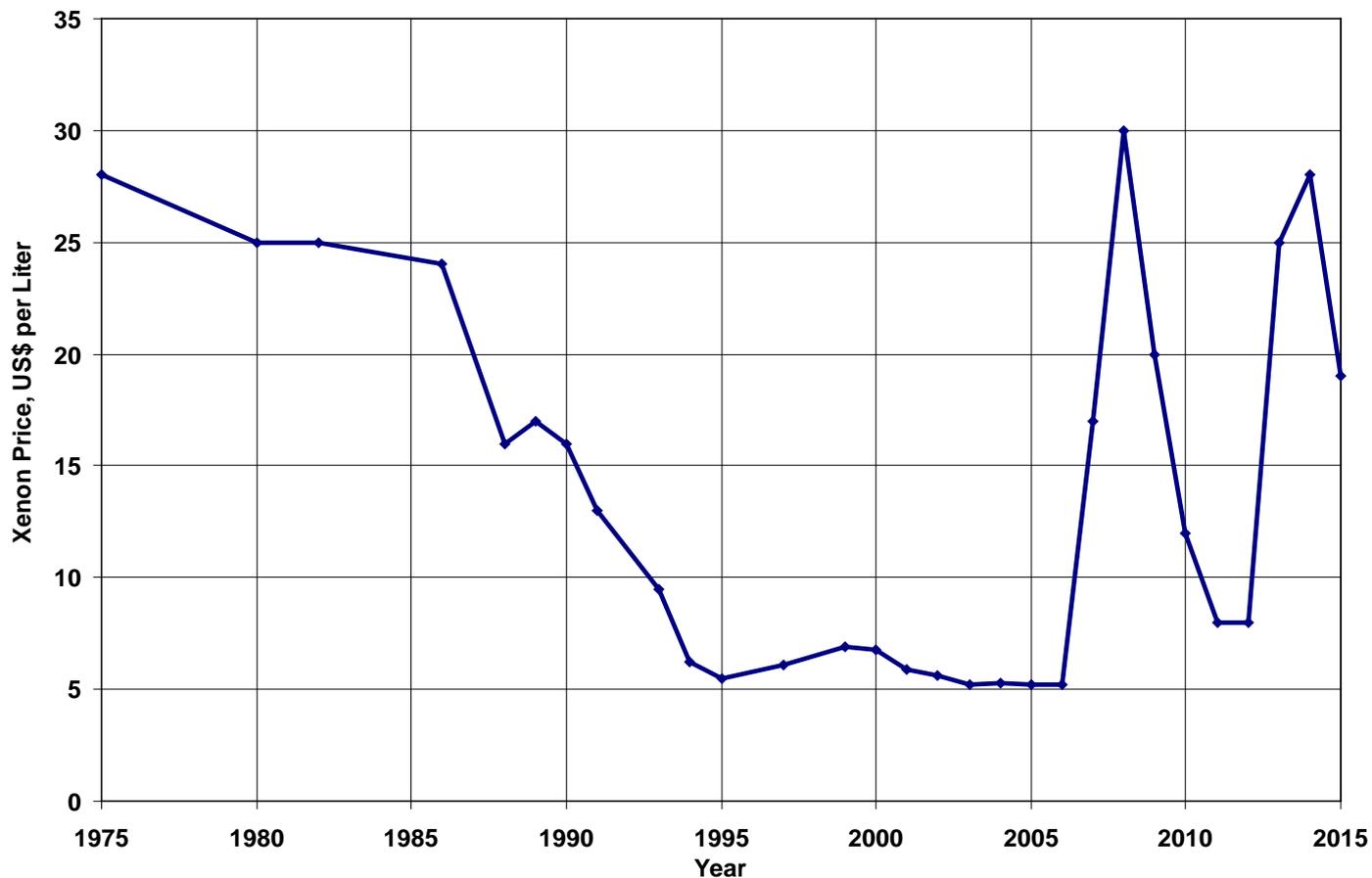
- Xenon price increases caused by decreases in supply and/or increases in demand
  - Xenon market reacts quickly with higher prices and reduces gradually as increased production comes on-line several years later

Increasing Xenon Production

- Designing xenon production capability into new ASU's is the most cost-effective way to increase xenon production capability
  - Plant down-time makes retrofitting existing ASU's unattractive
  - Limited number of ASU's may have built-in provisions for retrofit when ASU was built that can make retrofit more viable

- Minimum time required to add xenon production capacity is generally about 3 years
  - One year to find a suitable ASU project
  - Two years to construct the facility

- Lag between xenon market price spikes and increased production caused by 3 years to add xenon production capacity

Xenon Acquisition Approaches

- Two different xenon acquisition scenarios
  - Single mission application
    - ▲ Xenon contract duration ≤ 5 years
    - ▲ Xenon contract duration ≤ 10 years (same approach applies)
  - Large and/or multiple recurring exploration architecture elements
    - ▲ Xenon contract duration > 10 years

- Single mission application (xenon contract duration ≤ 10 years)
  - ARRM xenon load (up to 10,000kg) represents 19% of the 53,000kg of xenon produced each year
    - ▲ Need thought out acquisition approach to avoid price run-off!
  - Initiate procurement as early as possible minimizes price risk
  - Long-term commitment encourages necessary investments to increase supply that keep market prices in check
    - ▲ Government responsible for xenon contract even if mission cancelled via contract termination clause
    - ▲ In the event mission canceled, xenon delivered can be used for: other SEP TDM, NASA science missions, non-NASA SEP, non-SEP xenon users, and/or sold back

NASA Directed Mission Schedules

Mission	Phase A – Launch	Phase B – Launch	Phase C – Launch
SEP TDM BAA's	48	39	29
ARRM	69	60	44
18 NASA Directed	N/A	60	51

- SEP TDM aggressive, by design, to control cost
- ARRM reference schedule in family with other NASA directed missions
- Xenon acquisition approach is to initiate xenon procurement early to allow for smoother market adjustment
  - Encourage capital investment in production
  - Avoid short-term shortages in xenon
- Data that single purchases on the order of 3,000 kg can be absorbed by the market
  - Ability to absorb dependent on xenon availability and pricing factors outside the control of the mission
  - Use 3,000kg annually as a guide, but no guarantees!

Programmatic Constraints

Mission	Phase A – Launch	Phase B – Launch	Phase B ATP Contract Annual	Phase C – Launch	Phase C ATP Contract Annual
SEP TDM BAA's	48	39	1,240 kg (2% annual Xe)	29	1,770 kg (5% annual Xe)
ARRM	69	60	2,220 kg (4% annual Xe)	44	**3,160 kg (6% annual Xe)**
18 NASA Directed	N/A	60		51	

- Assume 6 months required for xenon contract competition and award
  - Contract annual average deliverable includes 6 months for acquisition
- If ATP for xenon propellant procurement at start of Phase C <u>and</u> funding to initiate procurement available at that time
  - Contract deliverable averages 6% global annual xenon production per year
  - Risk of negative impact on xenon market price and availability!
  - If delay in funding to initiate acquisition, the problem becomes worse
    - Minimum amount of funding required set aside to initiate acquisition process

Programmatic Constraints

Mission	Phase A – Launch	Phase B – Launch	Phase B ATP Contract Annual	Phase C – Launch	Phase C ATP Contract Annual
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- Assume 6 months required for xenon contract competition and award
  - Contract annual average deliverable includes 6 months for acquisition
- If ATP for xenon propellant procurement can be earlier (e.g., start of Phase B <u>and</u> funding to initiate procurement available at that time
  - Contract deliverable averages 4% global annual xenon production per year
  - Reduced risk of negative impact on xenon market price and availability
  - Possibility to reduce xenon load as mission definition refined

Long-Term Acquisition Approach (>10 years)

- For mission applications that can accommodate long-term xenon contract (greater than 10 years duration), the contract begins to approach duration over which the xenon equipment is amortized
  - Typical ASU (including xenon equipment) amortized over 15 years
  - Potential mission scenarios that could fit in this category
    - ISS-scale NASA mission
    - Exploration architectures with multiple (or refueled) high-power SEP elements that are staggered over many years

- Supplier could make necessary capital investments to provide guaranteed xenon supply at a fixed price (insulated from xenon market price fluctuations)
  - Government exclusive rights to xenon from one or more ASU's
    - E.g., 100 tons of xenon could be collected from 10 large ASU's over period of 10 years
    - Recurring Block 1a vehicle or refueling of Block 1a vehicle considered in paper

- The closer the xenon contract (government commitment) approaches 18 years (3 years production start-up plus 15 years amortized capital duration) the more viable this approach becomes
  - Such a long-term commitment seems unlikely currently given NASA budget uncertainty
  - May be a viable approach to consider in the future
  - Options to form government large-xenon buyer consortium for other multiple-ton xenon applications (dark matter experiments) if timing worked out

Conclusions

- Solar Electric Propulsion has represented about 10% of xenon market over past 20 years, but trends in propulsion and lighting may make propulsion a larger portion of the market in the future

- Global xenon production is 53,000kg annually

  - When demand exceeds supply, xenon market prices spike until the market can respond by increasing supply with a 3 year lag that can result in excessive pricing and limited supply

  - Data that market can absorb (depending on multiple other external factors) annual spikes in demand on the order of 3,000 kg

- For high-power NASA missions requiring multiple tons of xenon the recommended acquisition approach is to

  - Initiate procurement as early as possible minimizes price risk

  - Long-term commitment encourages necessary investments to increase supply that keep market prices in check

  - Programmatic constraints inhibit this recommended approach

    - Large procurements typically initiated in Phase C

    - Requisite funding at ATP to initiate procurement

    - 6 month acquisition duration

- For applications that can afford longer-term planning (> 10 years), exclusive xenon supply approach can provide xenon insulated from xenon market price but require long-term government commitment

Acknowledgments

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