XENON ACQUISITION STRATEGIES FOR HIGH-POWER ELECTRIC PROPULSION NASA MISSIONS

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ABSTRACT

The benefits of high-power solar electric propulsion (SEP) for both NASA's human and science exploration missions combined with the technology investment from the Space Technology Mission Directorate have enabled the development of a 50kW-class SEP mission. NASA mission concepts developed, including the Asteroid Redirect Robotic Mission, and those proposed by contracted efforts for the 30kW-class demonstration have a range of xenon propellant loads from 100's of kg up to 10,000 kg. A xenon propellant load of 10 metric tons represents greater than 10% of the global annual production rate of xenon. A single procurement of this size with short-term delivery can disrupt the xenon market, driving up pricing, making the propellant costs for the mission prohibitive. This paper examines the status of the xenon industry worldwide, including historical xenon supply and pricing. The paper discusses approaches for acquiring on the order of 10 MT of xenon propellant considering realistic programmatic constraints to support potential near-term NASA missions. Finally, the paper will discuss acquisitions strategies for mission campaigns utilizing multiple high-power solar electric propulsion vehicles requiring 100's of metric tons of xenon over an extended period of time where a longer term acquisition approach could be implemented.

INTRODUCTION

Solar electric propulsion (SEP) has been used for station keeping of geostationary communications satellites since the 1980s. Between 1995 and 2010 the number of geostationary communications satellites that utilize electric propulsion with xenon propellant for station-keeping increased more than ten-fold.[1,2] Solar electric propulsion has also been successfully used on NASA Science Missions such as Deep Space One and Dawn.[3,4] The xenon propellant loads for these applications have been in the 100's of kg range. Solar electric propulsion can provide an advantage over chemical systems because a higher specific impulse can dramatically reduce overall mass-to-orbit for certain applications. For missions beyond low Earth orbit (LEO), spacecraft size and mass can be dominated by the onboard chemical propulsion systems and propellant that may constitute more than 50 percent of the spacecraft mass. This impact can be substantially reduced through the utilization of SEP due to its substantially higher specific impulse. Recent studies performed for NASA's Human Exploration and Operations Mission Directorate (HEOMD) and Science Mission Directorate (SMD) have demonstrated that a 50kW-class SEP capability can be enabling for both near term and future architectures and science missions.[5]

To enable SEP missions at higher power levels, an in-space demonstration of an operational SEP spacecraft at power levels greater than current state-of-the-art has been proposed. This technology demonstration mission (TDM) will have direct applicability to a wide range of current and future NASA missions and should be extensible to future higher power systems that may require 100kW of power or more. Xenon is the preferred propellant for the existing state-of-the-art electric propulsion systems based on considerations including operational efficiency, storability, and contamination potential. NASA mission concepts for a 50kW-class in-space demonstration of high-power photovoltaic power systems, high-power propulsion systems, and large amounts of xenon propellant efforts have xenon propellant loads ranging from 100's of kg up to 10,000 kg. A xenon propellant load of 10 metric tons represents almost 20% of the global annual production rate of xenon. A single procurement of this size with short-term delivery could lead to a spike in the xenon pricing resulting in a disruption of the xenon market and making the propellant costs for the mission prohibitive. A careful, long-term approach may be preferred for the acquisition of 10 metric tons of xenon for NASA missions. NASA is also considering how a high-power SEP stage could be leveraged in different exploration architectures. Currently, two block upgrades to the ARRM vehicle are envisioned: a Block 1a capability with 150 kW of EP and 16 metric tons of xenon and a Block 2 capability with 265 kW of EP and 22 metric tons.[6] The applications for these high-power SEP stages, whether it be for multiple vehicles or refueling, could benefit from an alternate long-term xenon acquisition approach that becomes viable as xenon contract duration approaches or exceeds ten years.

This paper examines the status of the xenon industry worldwide, including historical xenon supply and pricing. The paper will provide updated information on the xenon market relative to previous papers that discussed xenon production and acquisition for NASA mission needs.[7] The paper will discuss the various approaches for acquiring on the order of 10 MT of xenon propellant to support potential near-term NASA missions considering possible programmatic constraints that would limit initiation of a xenon procurement very early in the project. Finally, the paper will discuss acquisitions strategies for multiple SEP vehicles that could be utilized in exploration architectures and larger NASA missions requiring 100's of metric tons of xenon.[6,8,9]

NASA HIGH-POWER ELECTRIC PROPULSION MISSION APPLICATIONS

The need for large amounts of xenon propellant for NASA missions was considered for both a single discrete mission such as the SEP TDM, and a larger, longer term need to support human exploration architectures. The xenon loads and timelines are sufficiently different that different acquisition approaches should be considered.

SOLAR ELECTRIC PROPULSION TECHNOLOGY DEMONSTRATION MISSION (SEP TDM)

The current state-of-art for high-power solar arrays are the rigid panels being used by high-power geostationary communication satellites with maximum total power in the 25-kilowatt range. The current state-of-art for electric propulsion is 5-kilowatt systems capable of processing 100's of kilograms of xenon propellant. In 2010 NASA's Space Technology Mission Directorate (STMD) began developing large, deployable photovoltaic solar array structures (SAS) for high-power production and high-power electric propulsion technologies.[6,10-14] The maturation of the critical technologies required for the high-power SEP vehicle has made mission concepts utilizing high-power SEP viable.

Over the last several years, as the SAS and electric propulsion technology developments were ongoing, there has been a parallel companion activity seeking to define an SEP TDM for NASA to implement in 2017-2019 timeframe. The objectives of the SEP TDM are to perform an in-space demonstration of these new SEP technologies with an integrated system, provide a high-power SEP transportation capability that provides a needed utility, and do so in a way that has direct extensibility to next-generation higher power SEP applications. Since 2012 a number of mission concepts, one such concept shown in Fig. 1, have been explored that meet the objectives of an SEP TDM with a range of xenon propellant loads from 100's of kg up to 3,400 kg.[15-17] In late 2012, an SEP TDM concept, the Asteroid Redirect Robotic Mission (ARRM), was identified as a 50-kW mission concept that could realize the full SEP capability envisioned by NASA utilizing the STMD SEP investments.[18-20]

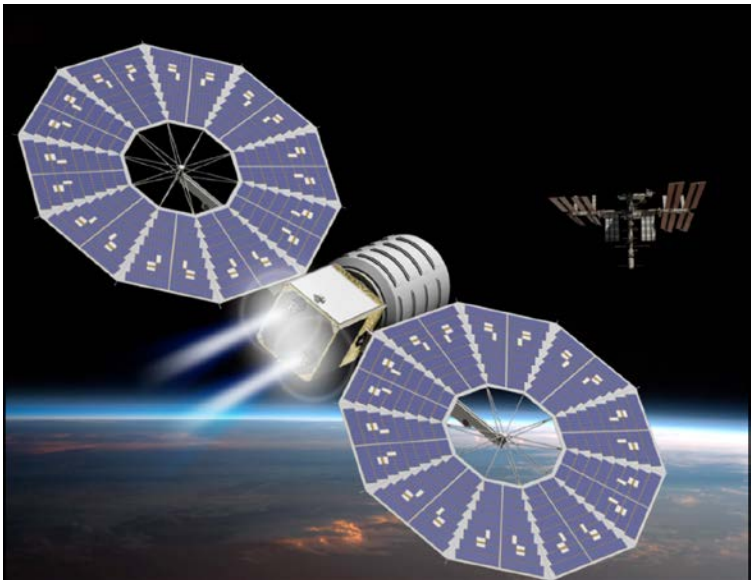

Figure 1. NASA (Internal) 50kw-class SEP TDM mission concept: High-power SEP transportation of 5,000 kg payload to E-M L2 [June 2012].

ASTEROID REDIRECT ROBOTIC MISSION (ARRM)

The Asteroid Redirect Robotic Mission (ARRM) is an SEP TDM concept that utilizes an SEP spacecraft to return a large amount of asteroidal mass from the surface of a larger asteroid, to an orbit around the Moon for subsequent access by a human crewed mission. The ARRM spacecraft concept, shown in Fig. 2, would utilize a 50kW-class spacecraft having a total mass of 15 metric tons including up to 10,000 metric tons of xenon propellant. The mission is based on the use of three strings of 12.5-kilowatt magnetically shielded Hall thrusters operating at up to 3000 seconds specific impulse integrated with 13.3-kilowatt power processing units. This concept would satisfy the SEP TDM objectives while simultaneously providing a transportation capability with the potential for follow-on NASA applications either as is or with further modifications referred to as block upgrades.

The ARRM schedule as currently envisioned has 69 months between the start of Phase A and launch with 44 months between the start of Phase C and launch. Xenon acquisition would be deferred until the beginning of Phase C. The procurement would take 5 months, and there would be only 39 months over which to stockpile and deliver the required xenon. Alternatively, if xenon acquisition could be initiated earlier there could be as many as 60 months available for selection and contract execution. There were also four other ARM mission concepts developed by industry based on adapting commercial spacecraft for the Asteroid Redirect Vehicle (ARV). Those four concepts had an average of 51 months schedule between ARV contract start and launch with an average of 38 months from the beginning of Phase C to launch.

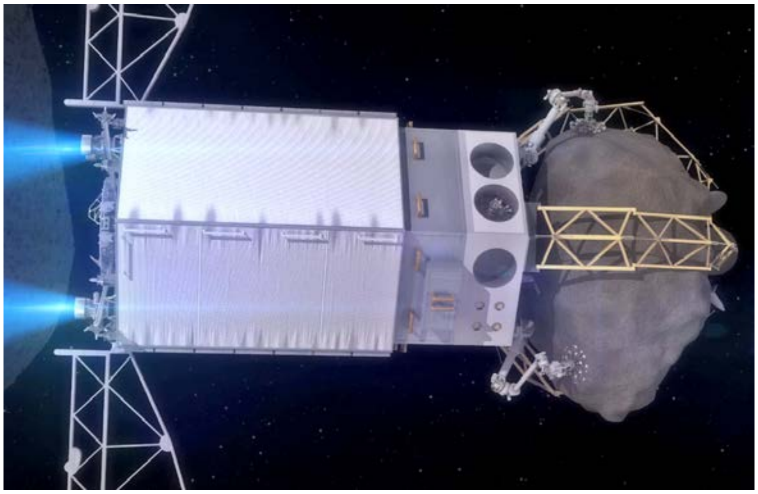

Figure 2. NASA (Internal) 50kW-class ARRM mission concept [Feb. 2015].

HUMAN EXPLORATION

NASA has long sought to implement larger, higher-power SEP platforms to perform a wide range of cross-cutting missions dating back to the 1970's.[6] NASA's Human Exploration Framework Team (HEFT) in 2011 introduced a "capability driven framework" approach that enables multiple destinations.[6] Once again, electric propulsion was identified as a desirable architectural element from an affordability perspective. The 300-kilowatt SEP vehicle concept developed by HEFT, shown in Fig. 3, had a total mass of 49,700 kilograms including 39,000 kilograms of xenon propellant.

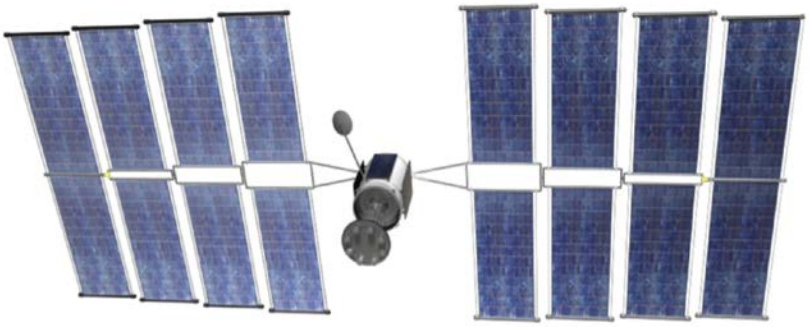

Figure 3. HEFT 300-kW SEP Vehicle Concept [2011].

The ARRM SEP vehicle and capability are being designed to be directly extensible to such follow on applications to maximize the value of the development. The vehicle is also being designed to have the capability of being evolved over time with minimal additional investments to support even more challenging future NASA applications. This reflects a "stepping stone" type of approach based on a high-power SEP capability that can be modified to perform increasingly more challenging mission without the need for additional new technologies. The stepping-stone approach to SEP capability evolution can provide a progression of increasingly higher power SEP spacecraft, referred to as "blocks", each conceived to meet specific NASA mission needs. The initial spacecraft, block 1, would be the SEP vehicle configuration used on ARRM with 50 kilowatts of power at the beginning of life, 40 kilowatts of electric propulsion, and 10,000 kilograms of xenon propellant.[6] The capability of block 1 will be sufficient not only for ARRM, but it could be used for deep-space science missions and follow-on Earth-orbital, cis-lunar, or lunar missions in support of human exploration such as moving logistics payloads and propositioning in-space assets such as habitation modules.

There is a set of later NASA mission requiring an SEP capability beyond the block 1 configuration where the same vehicle bus can be used with upgrades to specific subsystems. This configuration, referred to as block 1a, would utilize larger solar arrays with 190 kilowatts of power at the beginning of life, 150 kilowatts of electric propulsion, and up to 16,000 kilograms of xenon propellant is directly evolved from those used for ARRM and a higher power electric propulsion system achieved by simply adding additional thruster/PPU strings.[6] Since block 1 is being designed to accommodate this future growth there will be little or no changes to the bus structure and propellant storage systems. The block 1a SEP vehicle could supports additional missions leading towards a long-term goal of sending crew to the surface of Mars such as those in the "proving ground" or Mars moons. Proving ground missions would be the set of missions designed to become more Earth independent, demonstrating the set of technologies, systems, elements and operational capabilities required prior to embarking on human Mars surface missions. These missions would build upon the systems required for the ARRM mission and the crewed counterpart, asteroid redirection crewed mission (ARCM), prove systems on missions with longer durations away from Earth, eventually reaching the period needed for transits to and from Mars as well as any surface stay.[21,22]

More demanding missions and those requiring more propellant than block 1a would require block 2 SEP vehicles. Block 2 could support human missions beyond cis-lunar space all the way to supporting Mars surface missions through further increases in solar array size and electric propulsion system operating power.[23] There would also be a requirement for more xenon propellant storage capacity on block 2, but the SEP technologies and sub-systems could be directly derived from those demonstrated on ARRM. A notional block 2 capability is 300 kilowatts of power at the beginning of life, 265 kilowatts of electric propulsion, and 22,000 kilograms of xenon propellant.[6] To process the 265 kilowatts of electric propulsion power, development of 40-kW electric propulsion strings that would operate 8 of these strings in parallel is a relatively straight forward extension of the ARRM electric propulsion technology to higher-power.[24,25]

The different evolutionary steps in this block approach are shown in Figure 4 including a concept of how the solar arrays could be scaled. The left-hand side in the figure shows how the ATK MegaFlex array concept could grow the wing diameter sufficiently to achieve total power levels of up to 300 kilowatts with a pair of wings, each of which could be tested in existing thermal vacuum test facilities. The right-hand side in the figure shows how the DSS ROSA concept could evolve to 300 kilowatts by utilizing winglet modules similar in size to those used for the ARRM solar array wings in conjunction with a structural backbone in a configuration known as Mega-ROSA. There may be other combinations of scalability, modularity and block upgrades that could yield an even better evolution from a cost perspective, but mission specifics and the human Mars surface mission architecture will need to be better defined to permit further optimization.

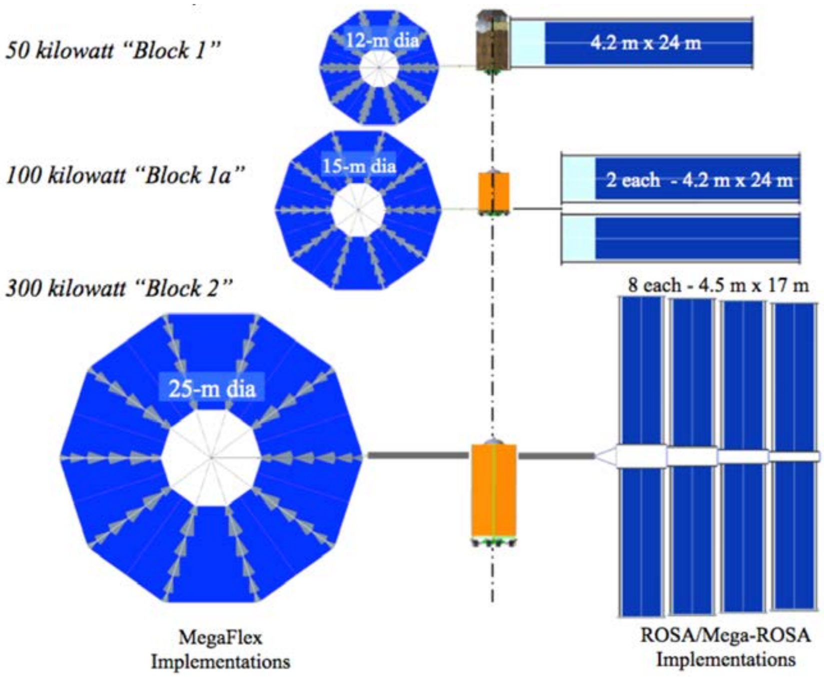

Figure 4. Conceptual stepping-stone evolution of higher-power SEP vehicles based upon the ARRM conceptual design (both SAS options shown).

PROGRAMMTIC AND SCHEDULE CONSIDERATIONS

There are programmatic constraints that limit when the xenon procurement could be authorized and a finite amount of time for contract selection that must be considered in the overall acquisition approach. Historically there is programmatic pressure that limits authorization for large procurements to the start of Phase C (mission Preliminary Design Review). Schedule estimates from seven SEP TDM concepts proposed under the BAA contracts, four ARRM concepts proposed under BAA contracts, the ARRM schedule as of MCR, data for directed NASA missions, and data from Mars Science Lab are summarized in Table 1.[26,27] It is estimated that the acquisition process, that is the contract selection process, would take approximately 6 months. As a result, the time between authorization to start the procurement to effective contract award date would be 6 months less than the duration between the mission PDR (KDP-C) and launch. Included in Table 1 are the xenon requirements per year of contract for the worst case propellant requirements of 3400 kg, 5000 kg, and 10000 kg of xenon for the SEP TDM (in-house and BAA's), ARRM BAA's, and ARRM (in-house), respectively. For a comparison to the schedule of a typical NASA directed mission, the 18 directed missions and MSL schedules are compared using the ARRM worst case xenon propellant requirement of 10,000 kg.

The data in Table 1 shows that the SEP TDM schedule was aggressive, by design to control cost. However, since the worst case xenon load to complete the mission was one third of that for ARRM the annual amount required is not the worst case. The in-house ARRM concept xenon load and schedule indicate 3,160 kg of xenon annually are required produced by the vendor. With annual production around 53,000 kg,[28] this represents 6% of the annual worldwide production. Since the ARRM schedule is in family with the other 18 directed NASA missions and MSL, the schedule is considered typical for a directed high-power SEP vehicle. It is not known whether a 6% increase in demand would disturb the market, but annual spot buys for up to 3 metric tons of xenon in recent years for in-space propulsion have been absorbed without triggering a run-off. However, there is a potential that the mission increased demand combine with other demand increases resulting in a price runoff. What is known is that this risk is lessoned if the annual increase in demand for the mission can be reduced. If the xenon contract acquisition start can be moved to KDP-B (Mission Definition Review), the annual xenon amount required decreases to 2,220 kg or roughly 4% of the annual worldwide production. It is recommended that the high-power SEP missions requiring many tons of xenon consider approval for xenon acquisition to begin at the start of Phase B. These missions should understand the motivation for this earlier approval and the differences between acquisition of chemical propellants, where long-term storage is not desirable, and xenon, where long-term storage is not an issue.

In addition to programmatic funding constraints, the phasing of the funding availability relative to the authority to procure the xenon, may lead to additional delays limiting the contract duration. This can happen if the project does not have the requisite procurement money to initiate the contact acquisition activity when authority to do so has been granted. In this scenario, authority to initiate xenon acquisition is provided at a major project gate, but the requisite budget available to initiate the procurement process is not provided until the start of the next fiscal year. This could further reduce the time available for procurement through xenon delivery. The project should plan to acquire xenon as early as possible in the project cycle and ensure resources are available immediately when authority is provided.

Table 1. NASA Mission Schedule Breakdown[26, 27]

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	29	1,770 kg
ARRM	69	60	2,220 kg	44	3,160 kg
ARRM BAA’s	51	N/A	N/A	38	1,870 kg
18 NASA Directed (Initial)[26]	N/A	60	2,220 kg	51	2,670 kg
MSL (Initial)[27]	59	N/A	N/A	39	3,640 kg

With the mission specifics and the human Mars exploration architectures still being defined, there may be multiple high-power SEP vehicles launched each with xenon propellant loads from 10 – 22 metric tons.[6,21-23,29] These missions and architectures may have the ability to plan longer in advance and/or take advantage of known xenon propellant needs over a duration of a decade or more. This could enable a new approach for acquiring large amounts of xenon over longer durations. If there is a sustainable NASA need, the assured demand could be sufficient for new, dedicated xenon supply to these missions independent of the global xenon market. For this approach to be viable, the xenon contract duration needs to approach the 15 year amortization of capital for the air separation unit and xenon extraction capital.

XENON AVAILABILITY

As shown in Table 2, xenon is found naturally in the atmosphere at a level of 87 ppbv (parts per billion by volume). It is not manufactured, but collected. Although the concentration of xenon in the air is only 87ppbv, or 390 ppbm (parts per billion by mass), there is a large quantity in atmosphere. Based on a total estimated mass of 5×10^{18} kg of air and a xenon concentration of 390 ppbm, the Earth’s atmosphere contains 2×10^{12} kg of xenon. Even if we consumed 20 metric tons per year for in-space propulsion (xenon not returned to the atmosphere), we could continue to do so for 1 million years. The amount of available xenon is limited only by how much is collected.

XENON PRODUCTION AND STORAGE

Xenon is collected as a secondary product of cryogenic air separation by air separation units (ASUs). These ASUs separate the components of air based on their boiling points using cryogenic distillation, which is a common method of production for oxygen, nitrogen, argon, as well as rare gases neon, krypton, and xenon. A typical ASU is shown in Fig. 5. With current global xenon production at 53,000 kg per year,[28] and most of this xenon ultimately being returned to the atmosphere, there is no shortage of xenon in the air.


Figure 5. Linde ASU in Kazincbarcika, Hungary.

Table 2. Composition of Air

Component	Concentration (%)
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)

There are numerous air separation plants around the globe. The ability to produce xenon is not inherently part of an ASU as it requires additional equipment beyond that required to collect oxygen or nitrogen. Whether or not the equipment necessary to collect xenon is part of an ASU depends on the xenon price when the ASU is planned and built. Worldwide, approximately 100 ASUs collect xenon.[30] Larger ASUs are most suitable for xenon collection because the capital cost per liter of production of xenon is lower at larger plants. Xenon normally comes from plants producing at least 2000 tons per day of oxygen.[2] During the separation of the air components the xenon is initially concentrated in the oxygen stream. It should be noted that because of its similar properties and greater abundance in the atmosphere, krypton is normally collected along with the xenon at a ratio near 10:1 krypton to xenon. Around 1.2 kg (200L) of xenon can be produced for each 1000 tons of oxygen produced.[31] As a result, an ASU with oxygen capacity of 2000 tons per day can collect 800 to 1000 kg of xenon per year.

The xenon/krypton mix that is collected at the ASU is typically further purified and separated using another cryogenic column at another location. This additional column will typically process gases collected at a number of ASUs. Because of the high value-to-transportation cost of the xenon and the high transportation-to-value cost of the oxygen, the ASUs are often built near the oxygen consumers and the xenon gets shipped long distances. These large ASUs often supply oxygen via pipeline to steel mills or petrochemical facilities.

Storage and transport of large quantities of xenon can easily be accommodated using approaches and equipment used in the supply of other gases. Tube trailers and tube banks (also referred to as Multiple Element Gas Containers, or MEGCs), as seen in Figure 6, are currently used to transport large quantities of gases on a regular basis. Xenon could easily be stored in such trailers. Trailers are typically constructed with six tubes that run the length of the trailer.

Each tube can be independently filled or emptied. The amount of xenon per trailer is limited to about 10 tons per trailer due to highway weight limits. For purely storage purposes each trailer could hold more, perhaps as much as 25 tons. A NASA internal estimate of the full-cost for storage of 10 tons of xenon for a SEP TDM is less than $500k, negligible compared to the xenon product cost. As a result, it may be desirable for NASA to store purchased xenon at a vendor's facility prior to use where it can be maintained and they have access for periodic filling. This also limits the government's liability as it can accept the final shipment of the total xenon amount at the loading site. As an inert gas, xenon is very stable and will not breakdown during storage. There is the finite possibility of contamination during extended storage (longer than three years). As a result, in this case the xenon would be re-analyzed prior to use and repurified if necessary.

Figure 6. Example of a tube trailer (left) and tube bank (right).

Other approaches can be used to collect xenon, but are not currently cost effective relative to producing xenon as a co-product of oxygen production. These alternate production approaches were considered in detail by Welle[31] and are no more practical now than when he considered them. It should also be noted that oxygen and nitrogen can be produced with pressure swing adsorption and membrane technologies. Pressure swing adsorption relies on differences in attraction between gases and a solid material. Membrane separation relies on differences in permeability of a membrane to effect the separation. Unfortunately plants using these technologies operate near ambient temperature and do not produce xenon or other rare gases as they do not appreciably concentrate the rare gases or provide a source of the gases at cryogenic temperatures.

TRENDS IN XENON PRODUCTION AND PRICING

Like most commodity products, the price of xenon depends on the interplay of supply and demand. At any given time, the supply of xenon available is a result of the installed capacity and its operating rate. This operating rate is driven by the oxygen requirements of the steel mills and other facilities supplied by the ASUs.

Xenon demand results from its use in a number of applications. It is used in the production of light bulbs, for making detectors, in plasma displays, for lasers, in dark matter research, as an anesthesia, and for electric propulsion. The annual xenon usage in each of these applications depends on production rates, changes due to technological developments, and xenon price.

As can be seen in Fig. 7, the supply of xenon has increased significantly during the past forty years. Since 1975 the demand and supply of xenon has increased ten-fold, as xenon usage has shifted from a specialty product used primarily for research and development to more of a commodity, relied on in a number of industries. A noticeable shift in the rate at which additional production was being added can be seen starting around 1990. This shift coincided with the increased supply of xenon from countries that had been part of the Soviet Union, an associated decrease in price, and the wider adoption in commercial applications. The more recent dip in supply between 2007 and 2010 was related to a slowing of the production of steel.

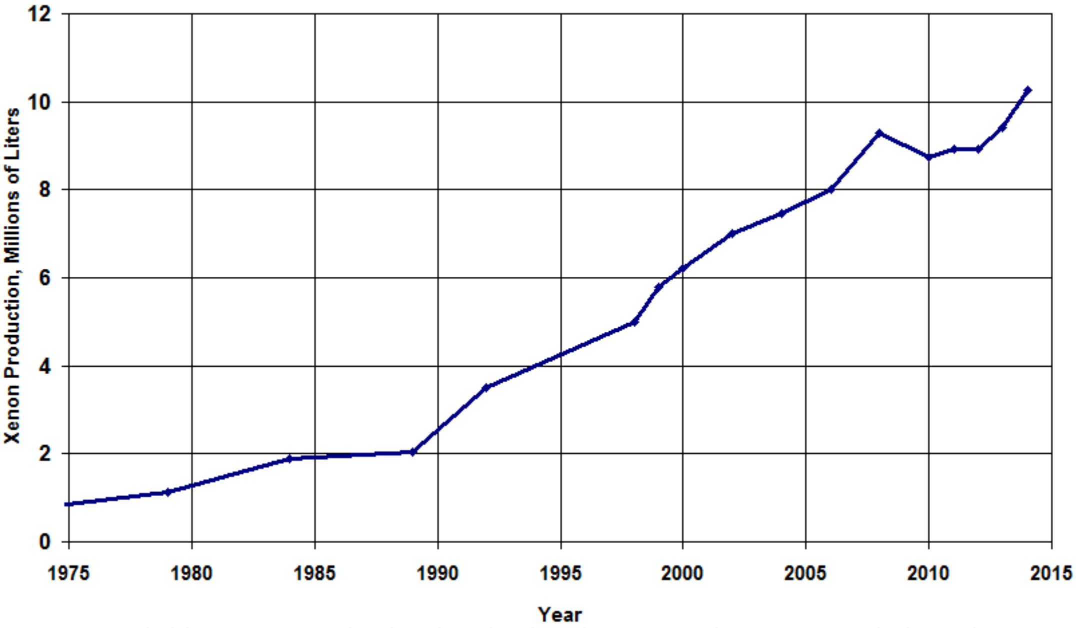

Figure 7. Worldwide Xenon Production (production data are estimates from Linde and Betzendahl[28])

Xenon for electric propulsion has been, and continues to be a relatively small part of the overall xenon market. Over the past 20 years the xenon demand for electric propulsion applications has represented approximately 10% of the xenon market with significant fluctuations year-to-year due to the historically small number spacecraft with relatively large quantities of xenon used by each. Although the portion of the xenon market utilized for electric propulsion has been relatively steady, the absolute amount used for electric propulsion has grown with the overall xenon market. This growth resulted from the increased use by geosynchronous communication satellite applications. Between 1995 and 2010 the number of geostationary communications satellites that utilize electric propulsion with xenon propellant for station-keeping increased more than ten-fold.[1,2] The amount of xenon used for each satellite has also increased as more satellites use electric propulsion for both station keeping and orbit apogee topping and orbit raising. This trend is expected to continue as all-electric geosynchronous communication satellites, offered by multiple satellite primes domestically and internationally, start to more fully penetrate this market.

Xenon price and availability is also affected by krypton price and demand because xenon is collected together with krypton using the same equipment. As previously stated, krypton and xenon are collected together in a ratio of about 10-to-1, krypton to xenon, and the capital and operating costs for the two gases are tightly interconnected. If xenon demand increases more rapidly that krypton demand, more of the production costs will need to be borne by the xenon market resulting in upward pressure on the xenon price.

Historic xenon pricing is displayed in Fig. 8. The price can be seen dropping as xenon transitioned from a specialty product to more of a commodity, with a large drop in the late 80's and early 90's as xenon that had been only sold in the Soviet Union became available on the world market. Note that these prices are not adjusted for inflation, making the reduction in price more dramatic. The price spike starting in 2006 is largely attributed to significant reduction in the amount of xenon being sold from ASUs tied to steel production in the former Soviet Union. Nearly simultaneously, in 2007-2008 new 45-nm silicon chip fabrication processes increased annual xenon demand by an estimated 14 metric tons. This illustrates how the xenon market reacts quickly with higher prices in response to rapidly increased demands as increased production capacity generally take several years to bring on line as discussed below.

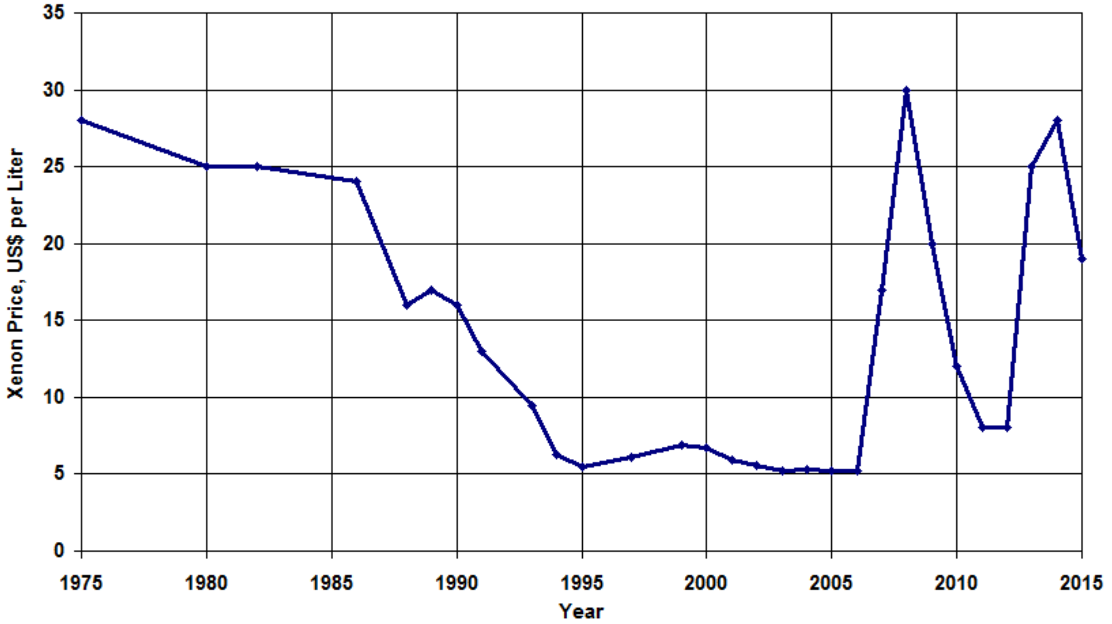

Figure 8. Xenon Market Price (typical price for customers with purchase volumes between 50,000 and 100,000 liters per year). Note that prices are not adjusted for inflation.

METHODS TO INCREASE XENON PRODUCTION

New xenon capacity can readily be added by integrating the necessary xenon (and krypton) collection equipment into new ASUs being built or by retrofitting existing ASUs with this equipment. Whether or not the equipment necessary to collect xenon is part of an ASU depends on the xenon price when the ASU is planned and built. New xenon capacity is installed when demand is sufficient to increase market prices to a point where the additional capital investment becomes cost effective. Xenon collection is capital intensive and historically the investment in the collection equipment has not been made if market prices do not support it. Additional xenon production capacity could readily be created at any time by retrofitting larger plants not currently collecting xenon. Retrofitting an existing ASU is generally easier if provisions for the retrofit were made when the ASU was built. Retrofitting ASUs not designed for xenon production requires additional engineering and capital costs compared to designing in the collection capability from the beginning, and more importantly will require significant down time at the facility stopping oxygen and/or nitrogen production during the retrofit. For these reasons retrofitting of existing ASU not designed for xenon production is not an attractive option for expanding xenon production capacity.

Designing xenon production capability into new ASUs is the most cost effective way to increase xenon production capability. The minimum time required to add xenon production capacity is generally about three years.[30] The three-year time period includes one year to find a suitable ASU project where xenon collection can be added to the design and two years to construct the facility. As a result, for applications requiring increased xenon availability a strategy of contracting for xenon production several years before final delivery is a recommended if reduced pricing is desired.

XENON ACQUISITION APPROACHES

To mitigate the risk of potential price increases resulting from a large xenon acquisition not requiring a long-term increases in production capability, purchasing incrementally over a number of years, thus allowing the market to adjust to the increased demand, is recommended. This allows the xenon market to adjust to increasing demand gradually as it generally has for the last thirty-plus years. For single-mission applications, this is likely the only viable approach. For applications with longer mission planning timelines and/or mission campaigns requiring recurring use of a high-power SEP, the timelines could get stretched such that an alternative approach that is independent of market fluctuations becomes viable. The acquisition approaches for large amount of xenon are discussed in this section.

SINGLE MISSION APPLICATION (XENON CONTRACT DURATION < 5 YEARS)

About 9.8 million standard liters (or 53,000 kg) of xenon are produced annually.[28] An SEP mission application such as the Asteroid Redirect Robotic Mission described earlier, with a requirement of up to 10,000 kg of xenon, would utilize approximately 20% of annual xenon production. A purchase of 10,000 kg of xenon with short-term delivery would almost certainly dramatically increase market prices. It is conceivable that 10,000 kg may not be available in a short period of time at any price. If sufficient product was available, the market impact could be such that the resulting price could be unaffordable by the mission. Fortunately, missions that will require these large quantities are likely to have longer lead times.

As previously discussed, the worst-case scenario for ARRM would require purchase of 3,160 kg (~6% of the annual worldwide production) on an annual basis. With an early start on the xenon acquisition the annual xenon amount required is reduced to 2,220 kg (~4% of the annual worldwide production). A discussion regarding the potential contract types for the xenon acquisition is beyond the scope of this paper. However, there are two competing issues with regard to how this acquisition could be structured. From the government's side, there is a desire to limit liability and shutdown costs in the event that the mission is canceled. This possibility is well known by the potential offeror's and, without a long-term commitment to the full amount, will discourage the necessary investments to increase supply sufficiently to keep xenon market prices in check. Splitting the purchase into three separate contracts also does nothing to encourage a long-term commitment to increased production capacity while also adding complexity if awards are given to multiple vendors. The most effect contract structure from a mission cost-risk perspective is to award a single contract to deliver the xenon at the end with partial payments made periodically as xenon is stock-piled. The contract termination liability would need to such that the possibility of cancellation would only have a minor impact on the contract. Thus the mission would essentially be committed to the full xenon required for the mission at contract start, even if the mission was cancelled. In the event that the mission was cancelled, the xenon could potentially be utilized by NASA or another government agency to recoup cost. This alternate government use could be another NASA SEP mission or a non-NASA applications such as a Department of Defense SEP mission or a non SEP use like the xenon dark matter ground detectors proposed for the LUX-ZEPLIN Experiment.[32] It may also be possible that the unused xenon could be sold back to the vendor for use in other programs, sold to other commercial electric propulsion users, and/or utilized for electric propulsion ground testing.

HUMAN EXPLORATION ARCHITECTURES (XENON CONTRACT > 10 YEARS)

To ensure xenon availability for even larger or recurring xenon propellant requirements, making a firm commitment to purchase over an extended number of years would convince a gas producer to make the capital investment necessary to produce the needed xenon on demand. This would essentially result in exclusive rights for the xenon from one or several ASUs. The cost of the xenon would therefore be fixed, or defined in advance for a number of years. The price would likely be based on production costs plus a margin instead of driven by the xenon market forces since the manufacturer has a guaranteed sale. For example, 100 tons of xenon could be collected from ten large ASUs over a period of ten years that is independent of market price. The amortization for capital for an ASU and xenon collection equipment is estimated at 15 years. For this approach to be financially attractive to providers, the stock-piling duration must begin to approach this duration. Exceeding roughly 10 years is used as an example.

The scenarios where this approach can be taken are very large (International Space Station scale) NASA missions with long planning durations or exploration architectures in which multiple, high-power SEP vehicles are required over the span of a decade or more. In either scenario, there would be a government commitment to a xenon contract where delivery of xenon can be accepted at least 10 years later or periodically over those 10 years (or longer). Such a long term commitment may be unlikely given the uncertainty in NASA planning and budgets. Even so, an example scenario will be considered that requires two Block 1A vehicles launched 5 years apart with the first vehicle launched 5 years after the ARRM launch. In this scenario, the government would commit to contracting for the xenon propellant for the two Block 1A vehicles in 2017. The total xenon propellant requirement would be 32,000 kg of xenon with delivery of 16,000 kg in 2025 and another 16,000 kg in 2030. The ARRM launch date is too soon for the contractor to bring new xenon production online considering the 3 year lag between the start of a new ASU with xenon production and the start of xenon collection. However, the following 32,000 kg could be provided by 3 large ASU's. With each ASU producing 1,000 kg of xenon annually, 15,000 kg would be available by 2025 with spot purchases of the remaining 1,000 kg. Similarly, 15,000 kg would be available by 2030. The further out the government is willing to commit to xenon production, i.e., the closer the timeframe gets to 18 years (3 years lag plus 15 years of production), the more viable this approach becomes almost regardless of the amount. It is also possible for different government agencies to combine forecasted xenon needs into a large xenon buyers consortium (NASA, DoD, DoE). The difficulty of this is other government agencies are subject to the same budget uncertainty as NASA.

SUMMARY AND CONCLUSIONS

NASA mission concepts developed for a 50 kW-class SEP demonstration, such as the Asteroid Redirect Robotic Mission, have a range of xenon propellant loads from 100's of kg up to 10,000 kg and a range of mission schedules. A multi-year strategy will be required for the acquisition of up to 10,000 kg of xenon without causing a spike in the xenon market price. One such strategy would be a single long-term acquisition over 3.5 – 4.5 years allowing the market to smoothly adjust to this new demand. If NASA xenon needs increase further, a longer term strategy for 10 years or more is recommended such that xenon could be provided from dedicated ASUs irrespective of global market price.

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