Cost-Benefit Assessment of Krypton and Xenon Recovery from Aqueous Reprocessing

Nuclear Fuel Cycle and Supply Chain

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ABSTRACT

This report provides an understanding of the costs and benefits of capturing krypton (Kr) and xenon (Xe) from the existing process of aqueous reprocessing of used nuclear fuel (UNF). The study accomplishes this with a market assessment of Xe prices and volumes today, coupled with a cost estimate of Kr and Xe capture out of cryogenic distillation within aqueous reprocessing.

The market assessment shows that the average price of Xe is about $60/L while the cost assessment finds the unit cost of Xe to range from $71.50/L to $131.13/L. This range is above the range of market prices today, but growing demand for Xe could cause prices to reach the range necessary to support the extraction of Xe from aqueous reprocessing. The assessment also shows that the market structure for Xe is one of oligopoly or very few suppliers to the Xe market. There is growing demand for Xe, particularly in medical applications like anesthesia, which could make Xe capture viable in the future.

Kr capture is a regulatory requirement for aqueous reprocessing, meaning that the costs are “sunk costs.” This research estimates a range of potential capture costs from $830/L to $1,523/L. Because these costs are sunk, unless there are any additional costs associated with the *sale* of Kr, it can be sold for additional revenue. Xe capture, however, requires additional capital expenditures and, as such, is not a sunk cost. While the expected costs of capture and storage of Xe are slightly higher than current market prices, the market experiences volatility and changes that make this opportunity valid for further research. Specifically, an investigation of the expected output purity of Kr and Xe from UNF aqueous reprocessing is warranted due to this factor’s impact on the sale price point.

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ACRONYMS AND ABBREVIATIONS

ARPA-E	Advanced Research Project Agency–Energy
DOE	U.S. Department of Energy
DOG	Dissolver off-gas
CURIE	Converting UNF Radioisotopes Into Energy
HLW	High-level radioactive waste
ILW	Intermediate-level radioactive waste
INTEC	Idaho Nuclear Technology Engineering Center
kL	Thousand liters
Kr	Krypton
LED	Light emitting diode
LEU	Low-enriched uranium
ML	Million liters
MRFWD	Material Recovery and Waste Form Development Campaign
MTHM	metric tons of heavy metal
N	"9"s in terms of purity
NE	U.S. DOE Office of Nuclear Energy
NTD	National Technical Director
PNNL	Pacific Northwest National Laboratory
PPM	Parts per million
Pu	Plutonium
SA&I	Systems Analysis & Integration Campaign
TNSC	Taiyo Nippon Sanso Corporation
U	Uranium
UNF	Used nuclear fuel
Xe	Xenon

COST-BENEFIT ASSESSMENT OF KRYPTON AND XENON RECOVERY FROM AQUEOUS REPROCESSING

1. INTRODUCTION

This study investigates the costs and benefits of capturing krypton (Kr) and xenon (Xe) during the aqueous reprocessing of used nuclear fuel (UNF) through cryogenic distillation. A market assessment of Xe was performed to provide a sense of marketplace value in alternative applications. Then, the study provides a costing methodology that was developed to determine the costs that capturing Kr and Xe adds to the unit cost of aqueous reprocessing. These results were then utilized to compute Kr and Xe capture costs on a per-unit basis.

The study was performed by a collaboration of two research groups from the U.S. Department of Energy (DOE) Nuclear Energy (NE). Researchers from the DOE-NE Systems Analysis & Integration Campaign (SA&I) and the Material Recovery and Waste Form Development Campaign (MRWFD) worked together to validate necessary technology assumptions that underpin the cost estimates and identify potential applications of Xe in the marketplace.

The approach the team followed was to first provide an overview of current market conditions for Kr and Xe using the Harvard Business School approach of Porter's Five Forces model. The market survey found that prices for Kr and Xe tend to hover around \$1/L and \$60/L, respectively. Then, to estimate the unit cost, the researchers followed a top-down, parametric cost analysis. The results of the cost analysis, where costs were estimated from capture and storage from cryogenic distillation, showed an estimated unit cost of Kr that ranges from \$830/L to \$1,522. For Xe, the cost estimate ranges from \$72/L to \$131/L.

The report proceeds with the market analysis in Section 2 and is followed by a description of the approach used to generate the cost estimate Section 3. Section 4 provides the cost estimates, and then Section 5 summarizes the cost estimates relative to the market value estimates and concludes the findings of the report.

2. XENON MARKET ASSESSMENT

Xe is a commodity that experienced modest performance in the global market during the early 2000s and 2010s. It is a rare gas that has historically been difficult to extract in large quantities, thus making the noble gas relatively expensive. For example, in the first quarter of 2023, Xe was sold for around \$60/L compared to Kr which was trading at approximately \$1/L (Wang 2023). A few major global gas producers are gearing up to invest heavily in Xe and Kr extraction facilities throughout the 2020s, namely, The Linde Group and Air Liquide (Wright 2023).

In 2022, the global supply of rare gases, like Kr and Xe, was disrupted following the Russian invasion of Ukraine. Ukraine is one of the world's largest suppliers of noble gas products (Athanasia and Arcuri 2022), and its current political struggles have caused many producers and manufacturers to seek more robust supply chains for critical inputs to their products. Figure 1 details how major world events affected the price of industrial gas products in the early 2020s.

This section employs a market analysis using a well-known framework called Porter's Five Forces. Michael E. Porter introduced the Five Forces Model in his article "How Competitive Forces Shape Strategy" (Porter 2008). The model breaks down the competitive landscape into five fundamental forces that determine the competitive intensity and attractiveness of an industry: competition in the market, barriers to entry, power of suppliers, power of customers, and threat of substitution. In the sections that follow, each of these are addressed in the context of Xe.

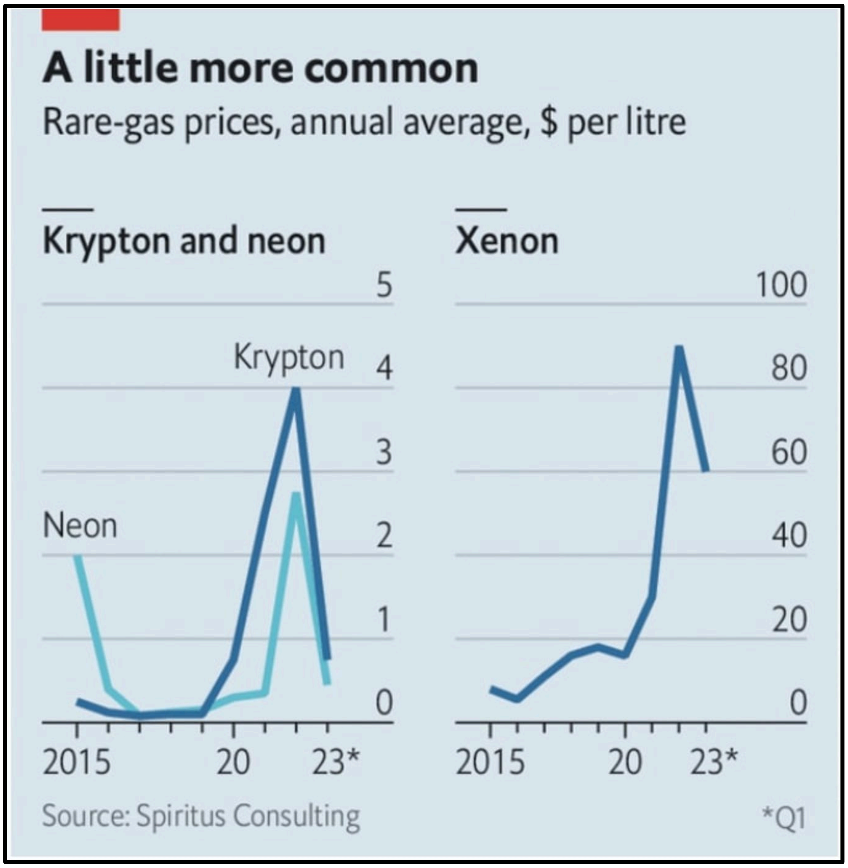

Figure 1. Global Xe prices surged during the 2020 COVID-19 pandemic and subsequent Russian invasion of Ukraine. Source: Wang (2023).

2.1 Competition in the Noble Gas Industry

The global noble gas market is large, with a diversified product offering. In 2022, it was valued at $2.60 billion with an expected compounded annual growth rate of 5.6% into 2030 (Grand View Research 2022). The competitive structure of the industry can be broken into several categories: product, application, end-user industry, and geography. Xe has strong activity in each category.

There are a handful of major Xe producers who operate globally and at large scale, namely The Linde Group (Ireland), Air Liquide S.A. (France), Air Products and Chemicals (United States), Cryoin Engineering (Ukraine), Taiyo Nippon Sanso Group (Japan), and BASF (Germany). These companies are large and distinguish themselves through branding, product launches, partnership agreements, and mergers and acquisitions.

In recent years, the industry has seen a shake-up with the merging of two of the largest players in the space. In 2018, The Linde Group merged with Praxair Inc., the third largest worldwide producer by revenue, creating the world's largest industrial gas supplier (Sullivan & Cromwell LLP 2018). Figure 2 details sale data for the largest noble gas producers in 2016 before the merger of Linde and Praxair. The merging of these two businesses is a prime example of how competition is structured within the noble gas industry. These strategies contribute to the formation of the noble gas oligopoly discussed further in Section 2.3.

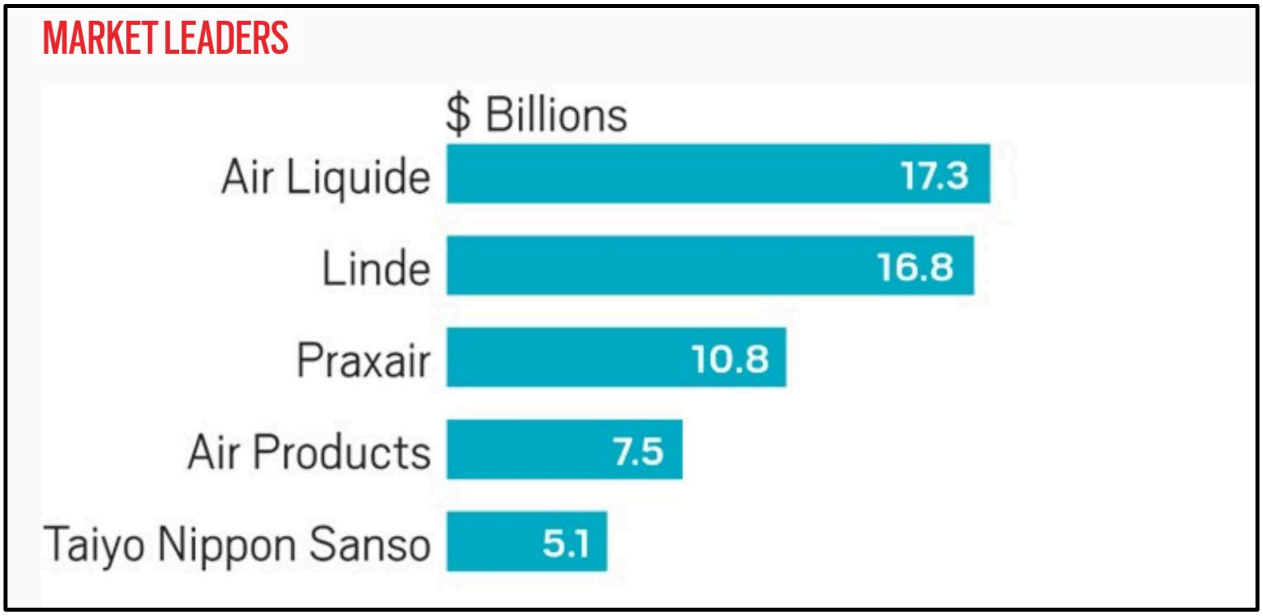

Figure 2. The combination of Linde and Praxair created the world's largest industrial gas provider. Source: Scott (2016).

2.2 Barriers to Entry

There are significant barriers to entry for the noble gas industry. Xe is a rare gas found in the atmosphere at a concentration of 0.086 parts per million (ppm) (Neice and Zornow 2016). Figure 3 shows the rarity of Xe compared to all the other gases that compose the atmosphere. The primary contemporary extraction method is cryogenic distillation, which is often part of a broader production process, making Xe an ancillary product. For example, in air that has been liquefied to produce 440 million short tons of oxygen, a maximum of only 120 million liters of Xe could be recovered As such, the startup costs to enter the industry are high and depend heavily on a firm's ability to produce multiple products at scale or develop a new extraction method that would lower costs and increase capture rates.

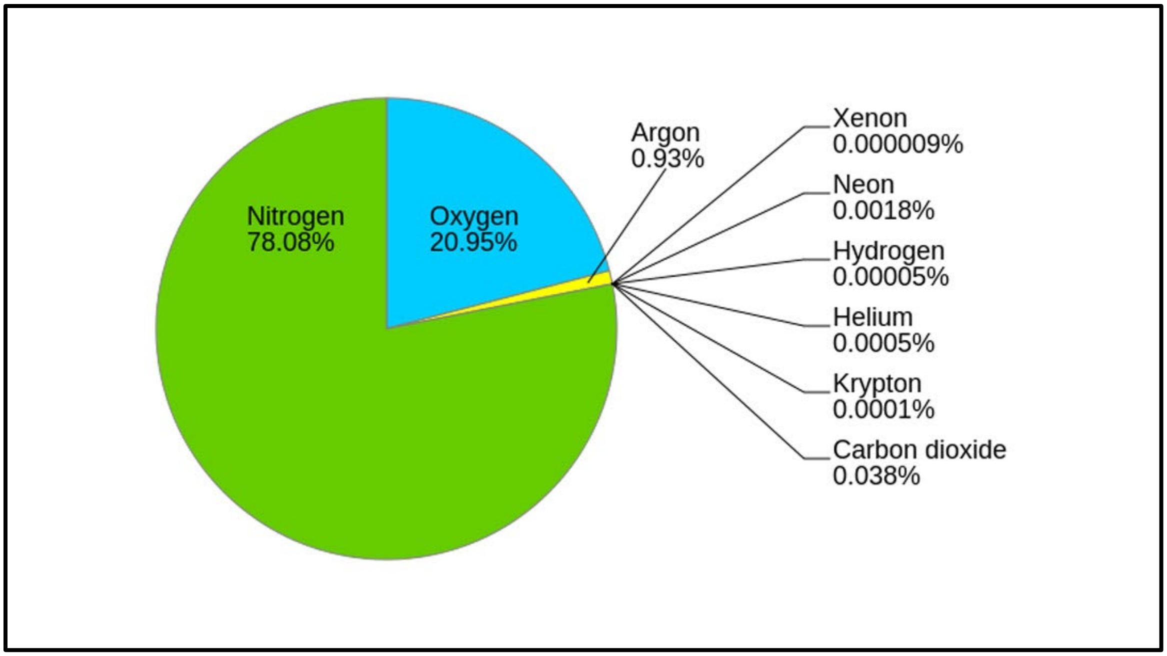

Figure 3. A breakdown of the gases that make up the atmosphere.

Given the scarcity of Xe and the apparent supply ceiling, many established industry producers are looking to either retrofit facilities with extraction capabilities or move into producing Xe as a primary product. In 2023, The Linde Group opened a new facility in Germany dedicated to the production of Xe and Kr (Wright 2023). With the expected increase in demand for chip manufacturing in Europe (Moore 2023), market watchers anticipate demand for these gases to increase.

The noble gas industry is capital intensive with high costs for building extraction facilities. There is growing pressure to increase supply chain reliability for Xe and other noble gases, which has industry players seeking out new construction and development opportunities. While the barrier to entry will remain high for noble gas due primarily to capital costs and specialized knowledge of extraction, there is an opportunity for new industry players with knowledge of these processes to enter the market.

2.3 Power of Suppliers

The bargaining power of suppliers can be characterized by the market's limited number of Xe producers and the specialized knowledge required to extract and refine the noble gas. See Figure 2 for the major producers in this market. These two factors are the basis of what forms the global noble gas oligopoly. Due to this, large suppliers benefit from factors including economies of scale, stable prices, and innovative research and development. Consequently, it can be quite difficult for newcomers to penetrate the market and pose a threat to larger firms.

However, as evidenced by the COVID-19 pandemic and Ukraine invasion, industry producers are subject to geopolitical and regulatory risks. These events caused price instability in international supply chains, compelling larger firms to invest in rare-gas-producing infrastructure. For example, in 2022, Taiyo Nippon Sanso Corporation (TNSC) announced that it would install Kr and Xe gas manufacturing units at the Fukuyama Plant of JFE Sanso Center Corporation. The memo released by TNSC states:

> *Although demand has been increasing globally in recent years, the reality is that [rare gas] supply is becoming tight…TNSC manufactures rare gases at Oita Sanso Center Co., Ltd. However, in light of the circumstances of demand and the government's policy, it has strengthened production in Japan in order to stably provide customers with rare gases and*

decided to newly install rare gas manufacturing equipment at the Fukuyama Plant of JFE Sanso Center Corporation to toughen the supply chain (Taiyo Nippon Sanso Corporation 2022).

The installation is expected to commence operation in early 2024 and will be capable of producing 2.6 ML per year of Kr and 210 kL of Xe. Other firms are investing in similar strategies, which depicts what the future landscape for industrial gas suppliers might look like. Overall, industry suppliers maintain significant bargaining power in the market but also must contend with risks that can weaken powerful positions.

2.4 Power of Customers

The power of customers in the Xe market can be characterized into distinct categories. Each category represents an aspect of the bargaining power that buyers have in the market. These advantages have a heavy impact on the market landscape.

The fact that Xe has a diverse array of applications heightens the bargaining power of the customers, especially for large-scale consumers. There are many different applications of Xe across industries. If a specific industry requires more Xe than others, it can exert bargaining power over small-scale operations in other industries. Also, given the inherent supply ceiling to the noble gas, industries with large bargaining power may force other industries to utilize substitute inputs, which can be difficult or nearly impossible when it comes to some applications. The next section goes into detail on market applications of Xe.

Purity requirements are also important within the market, which can be a significant bargaining tool for buyers in the Xe sector. Purity requirements can be used when dealing with Xe suppliers, who will typically refine and purify the gas on site at the capture facility. If suppliers cannot produce Xe with a minimum purity level, buyers may choose to go with different suppliers. Section 2.6 details how purity is defined by industry standards and the level of purity required for different applications.

Finally, the competitive landscape of the market is defined by the volume requirements of the consumers and the current available supply of noble gas. For Xe, this can be challenging since it is a rare and expensive gas to capture. This can be a weakness for buyers in the market who are faced with high Xe costs and are not able to switch to a substitute gas. Section 2.5 discusses the demand for different applications in the Xe market.

2.5 Market Applications

The Xe market is segmented into several categories: lighting and optics, medical, electronics, and semiconductors, as well as aerospace and aircraft. These broad categories account for many Xe applications in the market and drive much of the global demand for the noble gas.

In the medical sector, Xe is used for many different applications. For example, Xe has anesthetic properties and can be used as an inhalation anesthetic in medical procedures. It can also be used in functional magnetic resonance imaging to study brain function. These practices are relatively new and gaining traction due to research suggesting Xe’s therapeutic and neuroprotective benefits for treatment of neurological diseases (Zhang et al. 2021).

Similarly, the electronics sector uses Xe for various applications. An integral process to semiconductor manufacturing is photolithography; whereby a light is used to transfer patterns from a photomask onto a semiconductor wafer coated with photosensitive materials. Xe excimer lamps, which emit short-wavelength ultraviolet light, are employed to enhance the resolution and precision of this process. The high-energy photons from Xe excimer lamps enable finer feature sizes, which are essential for producing advanced integrated circuits (Sutter Instruments et al. 2013). Xe is also employed in ion beam sputtering processes, where a focused beam of Xe ions is directed at a target material to create thin films or deposit materials on semiconductor wafers. This technique is used to fabricate various thin-film structures and components in semiconductor devices.

2.6 Purity Requirements

In the global Xe market, purity requirements are critical as different industries and applications demand specific purity levels to ensure optimal performance and safety. The purity of Xe gas is typically expressed as a percentage, representing the proportion of Xe molecules in the gas compared to other impurities. This percentage is usually written in shorthand where "N" stands for "nine," followed by the number of nines, indicating purity. For example, N3 signifies 99.9% purity, N4.5 signifies 99.995% purity, N5 signifies 99.999% purity, and N6 signifies 99.9999% purity (BOC Limited 2023).

In the medical industry, where Xe is used for applications that directly affect patient safety, such as anesthesia, purity is critical. Xe used for these purposes must meet strict purity standards to avoid any potential contaminants. Purity levels of N3 or higher are typically required in the medical field, and N4 purity is often used (Sanders, Franks, and Maze 2003).

The electronics and semiconductor sectors often require high-purity Xe gas. For processes like semiconductor manufacturing, Xe must be free from impurities that could adversely affect the quality and reliability of precise electronic components. Purity levels in this industry often reach N6 purity or higher (Air Products and Chemicals Inc. 2023).

2.7 Volume Requirements

Demand for Xe is expected to rise as more applications are found in various industries. Volumetric needs for Xe vary, but growth is expected across many sectors. For example, in 2012, the lighting and optics industry consumed over 1.5 million liters of Xe (Betzendahl 2013). Since then, this industry has grown significantly and is expected to continue growing through at least the 2030s. Another example is the use of Xe in surgical anesthesia, where approximately 36 liters are required per patient (Neice and Zornow 2016). Considering about 234 million surgeries require anesthesia annually worldwide, covering all these surgeries would require over 3.5 billion liters of Xe (Neice and Zornow 2016). While this may be unrealistic due to current supply constraints, it highlights the significant market opportunity for noble gas producers as extraction and shipping costs decrease.

2.8 Threat of Substitution

Overall, Xe itself will experience little threat of substitution in the marketplace. It is difficult for many processes that depend on Xe to replace it with a different gas. This is partly due to the inherent "noble" (unreactive) characteristics of Xe in addition to the other noble gases. The processes requiring Xe have been well-refined and rigorously tested. The other noble gases have been extensively studied, and their properties well defined; they are not suitable substitutes for Xe with current technology.

The threat of substitution for Xe lies in the final goods created by producers consuming Xe. For example, Xe is used heavily in lighting and optics, but the rise of light emitting diode (LED) lights has imposed pressure on the Xe lighting product line. Another example is the use of Xe in medical applications. Given the supply ceiling for Xe, it would be difficult for the gas to take up most surgical applications and will need to share the market with different methods of surgical anesthesia.

2.9 Market Summary

The intricate dynamics of the global Xe market, as viewed through the lens of Porter's Five Forces model, paints a portrait of an industry in transition. The early 2000s and 2010s saw Xe maintain a modest growth rate, largely attributed to its rarity and the challenges associated with its extraction. However, recent geopolitical events, such as the Russian invasion of Ukraine, have brought to the forefront the vulnerabilities in the industry's supply chain.

Major industry titans like The Linde Group and TNSC have been prompted to make strategic investments targeting the enhancement of Xe and Kr extraction capabilities. This investment trend underscores the importance of ensuring supply chain stability, especially considering unforeseen geopolitical and global events that can disrupt operations. Competitively, the Xe market is marked by a few dominant players, evidenced by the merger of powerhouses like The Linde Group and Praxair Inc. Their scale and capability create a challenging landscape for potential new entrants, especially given the barriers to entry. This dynamic is further exacerbated by the industry's capital-intensive nature, the technical complexity of Xe extraction, and the inherent rarity of the gas. On the supply side, the power dynamic heavily favors the few established suppliers, primarily due to their specialized knowledge and the oligopolistic structure of the market. In terms of customer dynamics, the diversified applications of Xe across sectors, from lighting to medical imaging, confer varying degrees of bargaining power. With industries like semiconductor manufacturing and medical anesthesia displaying increased demand for the noble gas, the balance between supply and demand will be pivotal in shaping the future market trajectory. Last, while the unique properties of Xe protect it from direct substitution, its producers do face competition in end-use applications. For instance, the role for Xe in lighting may be threatened by the advent of LEDs, but its medical applications appear more secure.

In summation, the Xe industry's evolution, as illustrated by its competitive forces, reflects a marketplace that is both robust and vulnerable. The coming years promise growth, challenges, and the continual need for adaptation in the face of changing global circumstances.

3. COSTING APPROACH

The costs of cryogenically separating and capturing Kr and Xe from aqueous reprocessing of UNF depend on multiple factors, including the reprocessing plant's throughput, the concentration of target gases in the process input, and the desired purity of the output. This section creates a general baseline cost estimate for cryogenic distillation and capture of Kr and Xe and examines how costs may vary across use cases. While noble gas capture from nuclear fuel reprocessing is more commonly utilized to meet regulatory emission requirements, these byproducts could be captured and sold to the markets described previously to create a secondary stream of income and improve the overall economics for operators of reprocessing systems.

Cryogenic distillation was used successfully at Idaho Nuclear Technology and Engineering Center (INTEC) at Idaho National Laboratory to capture and separate Kr from Xe. The process was commercially available but was not optimized for tight emissions control. Development work was also completed in Belgium, France, Germany, and Japan (Goossen, Eichholz, and Tedder 1991). At the time of writing, to the authors' knowledge, the technology has not been used commercially for emissions abatement.

Due to the low amount of experiential data for the technology, direct cost estimates are not readily available. As such, estimates must be constructed from available data sources. The primary source employed for this report is the Converting UNF Radioisotopes Into Energy (CURIE) program's cost estimating tool, released under Advanced Research Projects Agency–Energy (ARPA-E) programming (Advanced Research Projects Agency Energy 2022).

Although the CURIE cost estimating tool covers both aqueous and pyro reprocessing—of which, aqueous is the focus of this report. This section of the CURIE tool (the line-item cost percentages) is itself based on estimates from "Fuel Cycle Advantages Resulting from the Significant Inventory of U.S. Spent Fuel" (Del Cul, Spencer, and Collins 2003). The line-item cost estimates in the CURIE tool are percentages of the total cost of used nuclear fuel (UNF) reprocessing and stay constant as the throughput level of the plant changes. As such, the CURIE tool and our derived results are capacity-agnostic (the percentages can be applied equally to plants of any size). While this is not an assumption that is likely to hold true in real applications, it is the best possible option given available information. The resultant percentage cost estimate must be applied to an example plant capacity to provide interpretable results.

Table 1. Costs for aqueous reprocessing of UNF.

Facility	%
Receiving	7.40
Mechanical feed preparation	12.40
Tritium confinement	3.47
Dissolution	7.77
Feed preparation	0.66
*Dissolver off-gas (DOG)**	3.97
Vessel off-gas	1.16
Solvent extraction – uranium (U)	1.32
Solvent extraction – plutonium (Pu)	1.48
Solvent treatment	0.99
Acid and waste recovery	1.82
HLW (high-level radioactive waste) concentration	0.99
ILW (intermediate-level radioactive waste) concentration	1.32
LEU (low-enriched uranium) purification	0.66
LEU conversion	3.80
Fissile conversion	2.15
*Head-end off-gas**	0.33
HLW solution storage	2.98
HLW solidification	4.63
Fissile product storage	0.33
Cladding storage	9.91
Fuel storage	11.42
*Krypton storage**	4.76
Cesium and strontium solidification and storage	9.52
Technetium solidification and storage	1.90
Iodine solidification and storage	2.85

Note: Line items partially or fully attributable to the capture, processing, and storage of Kr and Xe are denoted with an asterisk and italicized. Values do not sum to 100% due to rounding.

4. COSTING RESULTS

The examination of the CURIE cost tool and attribution of costs relevant to the Xe and Kr removal and storage (denoted as "studied costs") returned the following results:

- Kr storage accounts for 4.76% of total reprocessing costs. This line item is fully attributable to studied costs.
- The DOG system accounts for 3.97% of total reprocessing costs. The attributability of DOG costs to studied costs is indeterminant because the system also processes other gases like iodine. Internal estimates created in collaboration with MRWFD experts assessed that around half of the costs are attributable to Kr and Xe processes. Because of the challenge of directly attributing DOG costs to Kr and Xe, this report examines the full range from 0–4% with a midpoint of 2%. Three cases are examined, a low case where 0% of the DOG costs are attributed to study costs, a medium case (50%), and a high case (100%).

- The CURIE tool does not include costs specifically for the capture and storage of Xe—it is assumed that the system modeled in CURIE releases this element to the environment. Capturing Xe would add cost to the system; internal estimates made in collaboration with MRWFD experts approximate that the cryogenic capture system cost would be doubled to capture Xe at scale.
- As a consideration for future research, there is a possibility that the head-end off-gas line item may be attributable to Kr and Xe capture component costs.

Given this information, the percentage of total nuclear fuel aqueous reprocessing cost attributable to studied costs is estimated to be between 4.76% and 8.73% with a mid-range value of 6.75%. This percentage value is throughput agnostic (does not vary as the system capacity increases). To add the ability to capture Xe, the cost is expected to at least double, resulting in a range between 8.76% and 16.06% of total costs with a mid-range value of 12.41%. Note that the percentages presented for capture of both Kr and Xe are not double those presented for capture of only Kr because both the numerator (attributable costs) and denominator (total system costs) of the calculation are changed simultaneously through the addition of new line-item costs.

It is important to note that capture costs for commercial sale of Kr and Xe would likely be significantly higher than this range given that capturing higher quantities and qualities of the material is more difficult and expensive. It is assumed that the line item estimates presented in the CURIE tool are based on capture for regulatory requirements as opposed to commercial purposes.

Assuming a plant capacity of 300 metric tons of heavy metal (MTHM) per year (the same capacity as both the West Valley and Morris, Illinois plants—neither of which are currently operating) can give a perspective on the actual dollar costs of Kr and Xe capture as opposed to percentage values (American Nuclear Society 2015). An aqueous reprocessing plant specific to an advanced light-water reactor and U+Pu fuel with a throughput of 300 MTHM/yr results in plant capital expenditures of $8.26B using the CURIE tool. To provide a more comprehensive view of relevant costs, this report utilizes the total annual cost metric which combines operational expenditures and amortized capital expenditures. Table 2 expresses the cost range estimates for various operational strategies.

Table 2. Estimated capture costs of Kr and Xe based on regulatory requirements.

Annual Combined Costs	Range Low	Range Mid	Range High
Regulatory – Kr only	$41.2M (4.76%)	$58.4M (6.75%)	$75.5M (8.73%)
Regulatory – Kr and Xe	$75.8M (8.76%)	$107.4M (12.41%)	$138.9M (16.06%)

Combining the attributable annual combined costs with annual facility Xe and Kr production allows for an estimation of the per-unit production cost of the elements. Material balance tables (Jubin et al. 2016) were utilized to calculate the production of Xe and Kr from a facility with a throughput of 300 MTHM/yr. resulting in an estimate of 483.5k and 49.6k liters of Xe and Kr produced annually, respectively. Applying these values to the costs presented above and determining the attributability of costs to each of the elements based on moving from a Kr-only system to a system capturing Kr and Xe, the cost of producing each of the elements is given in Table 3.

Table 3. Estimated per-unit production costs.

Per-Unit Production Costs	Range Low	Range Mid	Range High
Xe	$71.50/L	$101.31/L	$131.13/L
Kr	$830.15/L	$1,176.34/L	$1,522.52/L

While the production cost for Xe is relatively comparable to current market prices for the product, the attributable costs of Kr are significantly higher than market prices. This is due to the low output of Kr as compared to Xe through the cryogenic distillation process—production of Kr is nearly an order of magnitude lower than that of Xe.

It is important to note that, in many cases, the capture of Kr from UNF reprocessing is required to meet emissions regulations. As such, it is not appropriate to compare the costs of Kr production to market prices because the costs are sunk costs. Instead, an opportunity for future research is to compare, if any, the additional costs associated with the sale of captured Kr to determine profitability. Xe, however, is not a sunk cost within this analysis because the addition of systems to capture the gas are optional. In situations where adding the ability to capture Xe does not increase the cost of DOG systems, this analysis shows that it can be profitable to capture and sell Xe when market conditions are favorable.

5. SUMMARY

The purpose of this report is to provide an understanding of the cost benefit of capturing Kr and Xe from the existing process of aqueous reprocessing of UNF. The study accomplishes this with a market assessment of Xe prices and volumes today, coupled with a cost estimate of Kr and Xe capture out of cryogenic distillation within aqueous reprocessing. The market assessment shows that the average price of Xe is about \$60/L while the average price of Kr is about \$1/L. The assessment also shows that the market structure for Xe is one of oligopoly with very few suppliers to the Xe market. The assessment shows growing demand for Xe, particularly in medical applications like anesthesia. The cost assessment finds the unit cost of Xe to range from \$71.50/L to \$131.13/L. This range is only slightly above the current range of market prices today, and with growing demand for Xe, prices could reach the range it would take to support the extraction of Xe from aqueous reprocessing. On the other hand, the estimated cost range for Kr is \$830.15/L up to \$1,522.52/L, which far exceeds the range of market prices for Kr. However, as the text notes, Kr capture is already part of aqueous reprocessing, so these are sunk costs, whereas the estimates for Xe are a marginal cost.

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