U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information
DE-FOA-0003306
on
Securing New Sources of Helium for Advanced Energy Applications

Introduction:

The purpose of this Request for Information (RFI) is to solicit input for a potential ARPA-E program focused on identifying transformative technologies across the helium-4 (“helium”) supply chain to decrease the delivered cost of helium from processes not dependent on natural gas production. ARPA-E is seeking information regarding alternative methods to safeguard future helium production in the United States and ensure helium availability for next-generation energy technologies. Specifically, ARPA-E is interested in identifying potentially disruptive concepts to: 1) develop innovative mapping technologies to locate new helium sources; and 2) produce helium using advanced separation technologies designed for novel sources and/or the enhancement of helium recovery and recycling.

ARPA-E is seeking input from analytical chemists, chemical engineers, geochemists, geophysicists, geologists, materials scientists, petroleum engineers, process engineers, subsurface engineers, and others with potentially relevant expertise. ARPA-E is also seeking input from prospective end-users of helium, including semiconductor manufacturers, welding technologists, and scientists and engineers working with superconducting materials (e.g., physicists, electrical engineers, biomedical engineers, aerospace engineers). This RFI is focused on soliciting input on methods that decouple helium production from natural gas production. The questions toward the end of this document are intended to assist relevant stakeholders in providing input on:

- Advanced identification, mapping, and quantification of new sources of helium, including co-locating potential geologic sources of hydrogen, subsurface seeps, geothermal reservoirs, and engineering methods to increase helium recovery from geologic sources;
- Potential separation methods for helium sources (e.g., membranes, electrochemical separations, and non-cryogenic methods); and
- Approaches for recovery and recycling of helium that resolve technical or economic constraints.

Areas Not of Interest for Responses to this RFI:

Work focused on basic research aimed purely at discovery and fundamental knowledge generation is not of interest.

RFI Guidelines:

CAREFULLY REVIEW ALL RFI GUIDELINES BELOW.

Note that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could be considered proprietary or confidential**.

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on March 15, 2024** Emails should conform to the following guidelines:

- Insert “Securing New Sources of Helium for Advanced Energy Applications - <your organization name>” in the email subject line.
- In the body of your email, include your name, title, organization, type of organization (e.g., university, non-governmental organization, small business, large business, federally funded research and development center [FFRDC], government-owned/government-operated [GOGO]), email address, telephone number, and area of expertise.
- In the body of your email, please also note which question(s) you are answering using the provided format (e.g., I.a, II.b).
- Responses to this RFI are limited to no more than 10 pages in length (12-point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential materials, designs, or processes.

Technical Background:

Helium is critical to many energy-related technologies, including semiconductor and fiber optics manufacturing, quantum computing, neutron detection, fission and fusion reactor cooling, and leak detection and analysis in gas processing facilities. The U.S. uses about 45 million cubic meters (m^3) of helium annually.[1] Approximately 50% of domestic helium usage is dedicated to industrial and scientific

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[1] Provornaya, I. V., Filimonova, I. V., Eder, L. V., Nemov, V. Y., & Zemnukhova, E. A. (2022). Prospects for the global helium industry development. *Energy Reports*, *8*, 110–115. https://doi.org/10.1016/j.egyr.2022.01.087

purposes related to energy.[2,3] Historically, the U.S. has been a major producer of helium, but its share of global production has fallen sharply in recent decades. A global helium shortfall of 70 million-110 million m^3 is anticipated by 2040, barring the successful construction of several large helium plants in geopolitically unstable regions of the world.[1,4] Rising demand for semiconductors due to increased electrification, as well as expanded uses of superconductors for advanced energy technologies, will likely result in the need for future helium imports. Thus, securing a robust domestic supply of helium is essential to ensure the U.S. maintains technological leadership in developing and deploying innovative energy technologies.

There have been four helium shortages within the past 20 years, leading to price spikes (Figure 1).[5] The curtailing of the U.S. Federal Helium Reserve and the fluctuating demand for liquefied natural gas has led to price instability.[6,7] Currently, helium is obtained in small concentrations from conventional natural gas reservoirs. Using today's technology, it is most economical to separate and recover helium from liquefied natural gas streams by integrating helium recovery into cryogenic processes. Such cryogenic facilities have high capital costs and retrofitting these facilities to include helium recovery is often prohibitively expensive.[8] As a result, the entire helium supply chain is dependent on fewer than 20 natural gas fields globally.

While the U.S. is currently a major producer of helium, the country's share of global helium production has decreased from more than 90% in the early 1980s to less than 50% in 2021.[9] This decrease is largely due to the emergence of new helium production facilities abroad. The sale of the Federal Helium Reserve has also depleted the domestic stockpile. Although domestic natural gas production has increased since 2007 due to hydraulic fracturing, the growth has not led to an increase in helium production because shale gas contains almost no helium.[10,11] The U.S. share of global production is

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[2] Siddhantakar, A., Santillán-Saldivar, J., Kippes, T., Sonnemann, G., Reller, A., & Young, S. B. (2023). Helium resource global supply and demand: Geopolitical supply risk analysis. *Resources, Conservation and Recycling*, *193*, 106935. https://doi.org/10.1016/j.resconrec.2023.106935

[3] U.S. Geological Survey. (2020, January). Helium. In *Mineral commodity summaries 2020*. USGS.gov. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-helium.pdf

[4] Cao, Q., Li, Y., Fang, C., Liu, R., Xiao, H., & Wang, S. (2022). Status quo and utilization trend of global helium resources. *Frontiers in Environmental Science*, *10*, 1028471. https://doi.org/10.3389/fenvs.2022.1028471

[5] Claudet, S., Brodzinski, K., Darras, V., Delikaris, D., Duret-Bourgoz, E., Ferlin, G., & Tavian, L. (2015). Helium inventory management and losses for LHC cryogenics: strategy and results for run 1. *Physics Procedia, 67*, 66–71. https://doi.org/10.1016/j.phpro.2015.06.012

[6] Burgess, M. (2023, June 2) *Helium 4.0: Expectations for a difficult summer*. Gasworld. https://www.gasworld.com/story/helium-4-0-expectations-for-a-difficult-summer/

[7] *Helium Shortage 4.0: What caused it and when will it end?* (2023, April 4). Innovation News Network. https://www.innovationnewsnetwork.com/helium-shortage-4-0-what-caused-it-and-when-will-it-end/29255/

[8] McElroy, L., Xiao, G., Weh, R., & May, E. F. (2022). A case study of helium recovery from Australian natural gas. *Case Studies in Chemical and Environmental Engineering*, *5*, 100200. https://doi.org/10.1016/j.cscee.2022.100200

[9] Kornbluth, P. (2021, November 25). *Helium removed from US critical minerals list.* Gasworld. https://www.gasworld.com/story/helium-removed-from-us-critical-minerals-list/

[10] Nuttall, W. J., Clarke, R. H., & Glowacki, B. A. (2012). Stop squandering helium. *Nature*, *485*(7400), 573–575. https://doi.org/10.1038/485573a

[11] U.S. Energy Information Agency. (2022, December 27). *Natural gas explained*. EIA.gov. https://www.eia.gov/energyexplained/natural-gas/

projected to fall to 35% by 2026, and the U.S. may eventually become a net importer of helium.[12] Without an increase in domestic production, there may be significant supply chain risks in the future, especially as helium demand increases with the onshoring of semiconductor manufacturing and expanded uses of cryogenic technologies.[13]

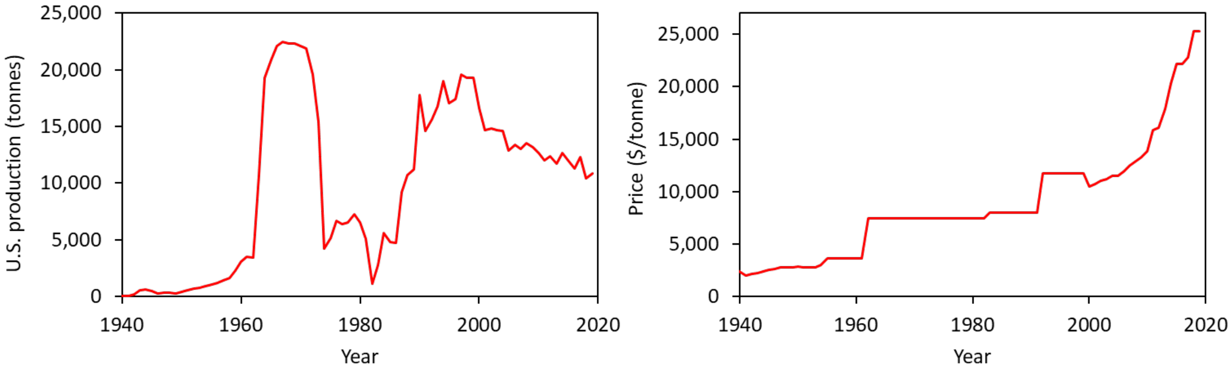

Figure 1. Domestic helium production (left) and global helium prices (right). Based on data from U.S. Geological Survey.[14]

RFI Questions:

The questions posed in this section are classified into several different groups as appropriate. Respondents may provide responses and information about any of the following questions. **ARPA-E does not expect any one respondent to answer all, or even many, of the prompts in this RFI.** In your response, indicate the group and question number you are responding to. Appropriate citations are highly encouraged. Respondents are also welcome to address other relevant avenues or technologies that are not outlined below, except for those that fall under the "Areas Not of Interest" described above.

I. New Sources of Helium

ARPA-E is specifically interested in information relevant to decoupling helium production from natural gas production. The geologic processes leading to the creation of helium and methane underground are distinct.[15] Whereas methane is formed from organic sources, helium forms in the subsurface via the alpha decay of uranium, thorium, and associated daughter products. As source rocks containing radioactive elements (typically granitic cratonic basement rocks) mature, helium slowly forms. Helium

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[12] United States Geological Survey. (2023, January 27). The USGS Seeks Public Comment on Helium Supply Risk. https://www.usgs.gov/news/national-news-release/usgs-seeks-public-comment-helium-supply-risk

[13] *Increasing investment in Chips production set to compound helium shortage for GC labs?* (2023, January 17). Peak Scientific. https://www.peakscientific.com/discover/news/helium-chips-act/

[14] National Minerals Information Center. (2023, November 9). *Helium Statistics and Information*. USGS.gov https://www.usgs.gov/centers/national-minerals-information-center/helium-statistics-and-information

[15] Danabalan, D., Gluyas, J. G., Macpherson, C. G., Abraham-James, T. H., Bluett, J. J., Barry, P. H., & Ballentine, C. J. (2022). The principles of helium exploration. *Petroleum Geoscience*, *28*(2), petgeo2021–029. https://doi.org/10.1144/petgeo2021-029

atoms remain trapped within mineral matrices and interstitial pore fluid until thermal events and fluid flow (e.g., groundwater, methane, carbon dioxide, nitrogen) perturb the trapped gas. Upon release, helium eventually migrates to traps or reservoirs where accumulation occurs.[15]

High-helium seeps have been found in the U.S. and abroad. In Yellowstone National Park, relatively high concentrations of helium have been discovered in gas streams released from geysers as supervolcanic heat liberates helium from underground seeps.[16] In New Mexico and Tanzania, high helium concentrations have been correlated with nitrogen-rich natural gas seeps.[17,18,19] Instances of helium in nitrogen-rich seeps may indicate that helium and nitrogen share similar liberation processes despite having distinct source rocks.[15,20] Geologic hydrogen gas, which can be generated from geochemical sources or through the radiolysis of water, can also migrate and accumulate within reservoirs distinct from its sources.[21] However, unlike hydrogen that can be microbially consumed or transformed, helium is inert and therefore would remain in reservoirs barring any leakage.

New diffusion modeling supports the feasibility of primary helium production in North America.[20] Several start-up helium companies have formed in recent years in Canada's Alberta and Saskatchewan provinces and in the U.S. Southwest.[22] While current helium prospecting is still nascent, these new findings suggest that current geophysical exploration principles can be adapted or modified to better identify helium deposits.

Identification and quantification of new helium sources will require locating mature source rock (via concentration of radioactive elements) and seeps and springs where helium may ultimately accumulate. This may include coupling helium exploration to unexplored or unexploited geothermal sources.[23] The accumulation in sedimentary and non-sedimentary rocks (e.g., in fractures of granite source rock) may require new extraction technology, as well as the expansion of small crude helium gathering systems. Efforts to quantify helium concentrations in subsurface seeps are also of interest, including efforts to quantify relative concentrations of helium-3 and helium-4.

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[16] Lowenstern, J. B., Evans, W. C., Bergfeld, D., & Hunt, A. G. (2014). Prodigious degassing of a billion years of accumulated radiogenic helium at Yellowstone. Nature, 506(7488), 355–358. https://doi.org/10.1038/nature12992

[17] Gluyas, J., Ballentine, C., Danabalan, D., Macpherson, C., Barry, P., Bluett, J., & Abraham-James, T. (2023, June). How to explore for helium. In *84th EAGE Annual Conference & Exhibition* (Vol. 2023, No. 1, pp. 1–6). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.2023101224

[18] Broadhead, R. F. (2005). Helium in New Mexico—geologic distribution, resource demand, and exploration possibilities. *New Mexico Geology*, *27*(4), 93–100. http://large.stanford.edu/courses/2011/ph240/tilghman1/docs/nmg_v27_n4_p93.pdf

[19] Halford, D. T., Karolytė, R., Barry, P. H., Whyte, C. J., Darrah, T. H., Cuzella, J. J., ... & Ballentine, C. J. (2022). High helium reservoirs in the Four Corners area of the Colorado Plateau, USA. *Chemical Geology*, *596*, 120790. https://doi.org/10.1016/j.chemgeo.2022.120790

[20] Cheng, A., Sherwood Lollar, B., Gluyas, J. G., & Ballentine, C. J. (2023). Primary N2–He gas field formation in intracratonic sedimentary basins. *Nature, 615*(7950), 94–99. https://doi.org/10.1038/s41586-022-05659-0

[21] Zgonnik, V. (2020). The occurrence and geoscience of natural hydrogen: A comprehensive review. *Earth-Science Reviews*, *203*, 103140. https://doi.org/10.1016/j.earscirev.2020.103140

[22] Kornbluth, P. (2023, May 30). *Kornbluth: North American helium start-ups are approaching first production*. Gasworld. https://www.gasworld.com/story/north-american-helium-start-ups-are-approaching-first-production/

[23] Chaudhuri, H., Sinha, B., & Chandrasekharam, D. (2015, April). Helium from geothermal sources. In *Proceedings of World Geothermal Congress* (pp. 19–25).

Another option may be recovering helium from process streams in chemical facilities. For example, helium can be recovered in air separation units (ASU) that produce neon. Ukraine formerly sold helium separated from co-product neon produced in very large ASUs that were part of a steel complex.[24] These facilities accounted for half of the global neon supply, which is now constrained. Helium recovery has been proposed for ammonia plants as well.[25] Once potential streams have been identified, it will be possible to evaluate existing or emerging technologies for helium recovery.

Section I Questions: Identifying and Quantifying New Sources of Helium

I.a. How much helium is the U.S. projected to require in 2035?
I.b. How can we improve advanced mapping and quantification of helium deposits independent of co-location with fossil fuels?
I.c. Is there a minimum quantity of radioactivity in source rocks that should be targeted for identifying helium deposits?
I.d. Given that geologic sources of hydrogen can share a similar origin to helium (i.e., originating from radioactivity), are there technologies being developed for geologic hydrogen that may aid in the mapping or discovery of helium-rich reservoirs? Would any of these technologies eliminate the need to map the radioactivity of source rocks to discover helium-rich reservoirs?
I.e. How well can existing hydrogen-mapping technologies discriminate between hydrogen and helium sources?
I.f. What is the state-of-the-art for quantifying spatial and temporal leakage of helium through subsurface seeps?
I.g. What technologies could improve the detection of helium in geothermal reservoirs?
I.h. What technological advancements are needed to co-produce helium with geothermal energy?
I.i. What industrial process streams are best suited for possible helium recovery (e.g., chemical facilities)? Why?

II. New Processes for Crude Helium Production and Upgrading

In the U.S., it is generally only economical to extract helium from natural gas streams when the helium concentration is at least 0.3% by volume due to the need for impurity removal, hydrocarbon extraction, and final cryogenics to purify helium to a crude grade (50-70% by volume).[26] Impurity removal and final cryogenics require large capital expenditures. Additional technical and logistical considerations, such as the total reserve base, also impact whether natural gas processing facilities pursue helium separation and resale. In Qatar's North Dome gas field, the largest singular natural gas field in the world, it is economical to extract helium from natural gas at concentrations as low as 0.04% because of the

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[24] Kravchenko, M. B., Hrudka, B. H., & Lavrenchenko, G. K. (2023). New technology to produce raw neon-helium mixture. *Low Temperature Physics, 49*(6), 743–752. https://doi.org/10.1063/10.0019432
[25] US Patent 8,152898 B2
[26] National Research Council (2000). 4: Helium Supply, Present and Future. *The Impact of Selling the Federal Helium Reserve* (pp. 40–48). The National Academies Press. https://doi.org/10.17226/9860

extremely large volume of gas being processed and liquefied in a centralized region.[27,28] Qatar is now the second largest producer of helium in the world despite the relatively low concentrations of helium in its natural gas streams. Liquefaction facilities in the U.S. process smaller volumes. When it is uneconomical to separate during processing, any co-extracted helium is directly vented to the atmosphere during natural gas extraction or combustion. The development of new technologies capable of economically extracting helium from new and potentially non-fossil feed streams, from more dilute sources, and from smaller processing volumes are therefore required to ensure a robust, domestic supply chain. Innovations capable of lower capital costs and enabling smaller extraction or purification facilities are of particular interest.

Producing helium from new sources may necessitate novel separation technologies, including new membranes, pressure swing adsorption systems, or cryogenic cooling systems, as well as downhole separation, or other yet-to-be-identified technologies. For example, novel adsorption processes have been suggested to recover helium from neon.[24]

In contrast to helium from global-scale liquid natural gas plants, potential future sources will likely produce smaller quantities of helium. New crude helium gathering systems and/or new small-scale processing plants may be required to upgrade crude helium to final purity. Aggregating and transporting helium from smaller, dispersed sources may require low-cost, small-scale compression and/or liquefaction systems, possibly integrated with crude helium production and/or system upgrades.

Section II Questions: Helium Production via Novel Processes

II.a. What gases are expected to be co-located with helium derived from new sources? What information is needed to better identify the gases?
II.b. What are current and anticipated separation challenges for various helium streams?
II.c. How does the energy required for cryogenic separation methods compare to other applicable separation methods?
II.d. What potential hydrogen-helium separation methods exist, including engineered membranes, electrochemical separations, or other unexplored non-cryogenic methods?
II.e. How might chemical reactions be utilized to react non-helium species (i.e., taking advantage of the inert nature of helium)? How would these approaches transform other species to leave a purer stream of helium?
II.f. If helium-3 is contained in the helium-4 stream, are there new technologies that could be developed for the separation of helium-3 from helium-4?
II.g. How can we develop new systems for collecting, processing, aggregating, and transporting helium at small scales?

III. Recovery and Recycling

ARPA-E seeks information on innovative concepts in new recycling and conservation technologies,

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[27] National Research Council. (2010). 4: Helium Sourcing and Reserves. *Selling the Nation's Helium Reserve* (pp. 71–86). The National Academies Press. https://doi.org/10.17226/12844

[28] Qatar: start-up of world's largest helium unit. (December 5, 2023). Air Liquide. https://engineering.airliquide.com/qatar-start-worlds-largest-helium-unit

drastic capital reductions, and step changes that lead to recycling and conservation technology adoption. Helium is a non-renewable resource that escapes the earth's atmosphere once exhausted into the air. While many applications of helium—including cryogenic cooling of superconductors—utilize recirculation systems, helium may still be lost due to leaks and inefficiencies in recirculation and recovery processes. It would be beneficial to increase recovery and recycling rates for all helium applications. Helium is directly lost when used for semiconductor manufacturing and welding, rocket pressurization for space launches, and in some scientific research applications.

Recycling approaches include helium recycling during atmospheric venting collection, nitrogen rejection and helium recovery, and new methods to recover gas streams with at least 0.5% helium. Transporting, capturing, and re-liquifying helium on-site are other avenues for recycling. End users have pursued the recovery of helium purge gas during rocket fueling operations or during the manufacturing of semiconductors. These approaches highlight the increasing technology portfolio of conservation and recycling, but the need for large initial capital investments continues to be a barrier to adoption. Helium conservation may be enhanced by developing novel refrigeration systems to reduce helium demand in cryogenic applications. For example, helium-neon mixed refrigerants have been proposed for hydrogen liquefaction.[29] Mixed refrigerants containing neon, hydrogen, and helium have been proposed for superconducting transmission lines.[30]

Section III Questions: Technologies for Recovery and Recycling

III.a. What is the range of leakage for different types of recirculation systems? What percentage of helium is utilized within recirculation systems versus what is directly consumed/lost by these processes?
III.b. What options are available for overcoming technical or economic limits to current helium recovery processes?
III.c. What options are available for increasing helium capture, recovery, and/or recycling for specific processes? What techno-economic gaps exist for helium capture, recovery, and/or recycling for specific processes?
III.d. Can alternative gases be used in conjunction with helium to reduce helium demand while still meeting the physical and chemical properties of pure helium?

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[29] Bi, Y., & Ju, Y. (2022). Conceptual design and optimization of a novel hydrogen liquefaction process based on helium expansion cycle integrating with mixed refrigerant pre-cooling. *International Journal of Hydrogen Energy, 47*(38), 16949–16963. https://doi.org/10.1016/j.ijhydene.2022.03.202 .

[30] Kloeppel, S., Dittmar, N., Haberstroh, C., & Quack, H. (2017, February). Mixed refrigerant cycle with neon, hydrogen, and helium for cooling sc power transmission lines. In *IOP Conference Series: Materials Science and Engineering* (Vol. 171, No. 1, p. 012019). IOP Publishing. https://doi.org/10.1088/1757-899X/171/1/012019