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^{3}He Supply Won't Meet Demand (Or Will It?)

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Is there a confrontation between a growing demand for helium-3 and an inelastic supply[1]? Does it matter?

Existing supply of ^{3}He

At present, ^{3}He (the light stable isotope of the far more plentiful ^{4}He) is supplied almost exclusively from the decay of tritium. Because tritium—^{3}H, the mass-3 isotope of hydrogen—beta decays to ^{3}He with a half-life of 12.3 years, there has been an ample supply of ^{3}He from the ^{3}H the National Nuclear Security Administration—NNSA—of the Department of Energy—DOE--maintains in its nuclear weapons

The DOE has sold ^{3}He at annual "auction," at a stable price of $85/L-STP, most recently in August, 2008. From 2004-2008 DOE Isotopes Program—"DOE IP" distributed about 30 kL/yr, and in 2008 the Oak Ridge Spallation Neutron Source (SNS) received 35 kL outside the Isotopes Program, depleting the inventory. According to (1), DOE-IP is expected to be able to supply a total of 86 kL for the period FY 2009-2014, or about 14 kL/y. Kouzes notes a combined requirement for DOE, DHS, and DoD of 100 kL for this period and quotes an estimate by the firm GE Reuter Stokes that the annual ^{3}He demand is 40-70 kL.

Potential sources of ^{3}He

^{3}He is found in atmospheric helium (He is 5.2 ppmv in air) to the extent of about 1.34 ppm. It is present at about 0.2 ppm in helium separated in purifying U.S. natural gas for distribution in order to improve the heating content of the raw NG, of which helium is a diluent to the extent of 0.2-2%. Some 130 million cubic meters of helium are supplied by the United States annually from this source; the total content of ^{3}He at 0.2 ppm is thus 26 kL/yr.

[1] R.T. Kouzes, "The He-3 Supply Problem," PNNL-18388, April 2009.
http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18388.pdf
This is a good description of He-3 supply and demand, and of some alternatives for both.

The 48 CANDU-style (Canadian Deuterium Uranium) power reactors throughout the world constitute a potential source of ^{3}He. CANDUs have a moderator of heavy water to thermalize the neutrons to fission natural or slightly enriched uranium, and despite the small capture cross-section of deuterium, a substantial fraction of the neutrons are captured in the deuterium to form tritium. For some reactors, that tritium is normally separated from the heavy water for health and safety reasons and stored as titanium-tritide, where it decays to ^{3}He at the usual rate of 5.5% per year. It is estimated that about 80 kL of ^{3}He are stored in titanium-tritide cylinders, and the arising rate is several kL/yr of ^{3}He.

Uses of ^{3}He

^{3}He has long been used as a near-ideal counter of thermal neutrons because of its very large capture cross section of 5330 barns (1 barn is 10^{-24} cm^2). ^{3}He "proportional counters" have minimal sensitivity to gamma rays, and the high sensitivity to thermal neutrons means minimal time required for a measurement—particularly important for detecting fission neutrons from clandestine plutonium at personnel or vehicular portals. The Department of Homeland Security is planning to use some 20 kL/yr for this purpose, at an expected price of some $125/L. Similar amounts are expected to be used by the Defense Department's DTRA (Defense Threat Reduction Agency), and in other programs.

Modest amounts of ^{3}He are used for scientific research—some in unique applications such as refrigeration to the temperature range of 300-900 milliKelvin and for ^{3}He dilution refrigerators at much lower temperatures. And of course ^{3}He is the subject of scientific research as is ^{4}He, with unexpected results such as the discovery of "super-solid" phenomena. Large amounts are used in high-end neutron counting research, for instance at the SNS, and around the world at similar facilities.

In recent years, hyperpolarized ^{3}He has become a valuable tool in medicine—for non-invasive NMR imaging of the gas space of the human lung. Down-hole neutron counters in the oil and gas industry account for ~3 kL/yr of ^{3}He demand.

The gap between supply and demand

Some 20 kL of Russian ^{3}He is believed to have entered the U.S. market in 2007, but current U.S. source of supply is ~14 kL/yr from decay of U.S. weapon tritium and whatever is released from the DOE store-- with ~25 kL expected to be released before year-end 2009, leaving ~21 kL in inventory.

If the projected ^{3}He annual usage for the coming year and beyond is ~65 kL, with a supply of ~14 kL/yr, it is likely that there will be unsatisfied demand.

Reducing demand for ^{3}He

An efficient market for ^3He could have helped to bring demand into accord with supply—reducing the former and over the long term, increasing the latter. But by how much? The answer depends on price and time. As the "shadow" price of ^3He increases (as with any "good"), some users will find that it is too expensive a component of the product or service that they wish to supply to the ultimate customer, and will leave the market.

Other users will substitute other goods—less efficient or of higher cost for a given performance. In the case of ^3He neutron counters, there are long-established competitors that will provide adequate performance at, perhaps, higher cost or larger size, or with more hazard. For instance, high-pressure boron-trifluoride (BF_3) has somewhat lower detection probability than ^3He, even if made with the rarer isotope of boron—^{10}B—in view of ^{10}B's thermal neutron capture cross section of 3840 barns; they also require much higher voltage than do ^3He counters. BF_3 counters typically use ^{10}B enriched to 90% purity. But shipping regulations would require BF_3 above atmospheric pressure to use adequate means for reducing the health hazard of BF_3 leaks. At present, ^3He proportional gas counters are available up to 10 atm filling, while BF_3 is commonly listed at pressures of 0.9 atm or below. Fitting the BF_3 counter assembly with means of nullifying the hazard of leaks could allow BF_3 neutron detectors to replace some 40 kL/yr of ^3He demand.

Without exceeding 0.9 atm of BF_3, counter assemblies of equivalent performance to ^3He could be built with larger amounts of polyethylene neutron moderator and some 3-fold counter tubes at higher cost than with ^3He at $125/L, but perhaps lower cost than with ^3He at $500/L.

Furthermore, counters can be built either in the conventional cylindrical configuration of a proportional counter filled with argon or other convenient gas, with a high sensitivity to thermal neutrons provided by a thin layer of ^{10}B or ^6Li on the inner wall of the cylinder, with capture cross sections of 3840 and 940 barns, respectively. Such a counter (perhaps a tube cluster or internally finned tube) might have a sensitivity about equal to that of the equivalent ^3He counter for thermal neutrons, since the metal-layer counter relies on one of the charged reaction products emerging into the gas fill to provide an electrical signal.

Other approaches are probably at a less mature stage than the boron-lined proportional counter tubes or doped plastic fiber detectors. There are many approaches to spiking a polyethylene moderator with an isotope that absorbs most of the thermalized neutrons and produces an electrical signal, but commercial availability and good knowledge of the cost are some years off.

Which is to say that the demand curve (demand vs. price) for ^3He is ill-defined.

Quite unusually, the demand curve is reversible to some extent, in that at a high enough price, ^3He could be recycled from existing counter tubes to satisfy uses of higher value.

Increasing the supply of ^3He

^{3}He can be produced as a spallation fragment but the cost is considerably greater than that for production of ^{3}H (tritium) that becomes ^{3}He with a delay (half life) of 12.3 years, IF the tritium is produced as a byproduct of electric power production. This is a well established process using Tritium-Producing Burnable Absorber Rods (TPBAR) in the Watts Bar nuclear-power-generating reactor. If one assumes 0.2 spare neutrons available (to be captured in ^{6}Li) per fission of 180 MeV heat production, this is one ^{3}H per 900 MeV or one mole per 86 TJ of heat produced. At 3GWt, a modern 1-GWe reactor yields 94,000 TJ/yr. So just about 1100 moles or 3.3 kg of ^{3}H could be produced annually in one Watts Bar reactor. In the steady state, this would yield about 25 kL/yr of ^{3}He, but initially this source of supply would grow linearly at a rate of 1.4 kL/yr^2.

As indicated, CANDU reactors have accumulated some 80kL of ^{3}He in the titanium-tritide cylinders, but there has apparently not been a persuasive business plan for the reactor operator to separate the ^{3}He. It would make sense for the United States DOE to help with the disposal of the separated tritium by buying the titanium tritide cylinders, producing ^{3}He as a byproduct. The United States might provide tritium-reduction facilities to reactors that do not have them, in return for removing much of the tritium and ^{3}He.

The 130 million cubic meters per year of helium supply in the United States contains about 26 kL of ^{3}He. At $4.25 per cubic meter, the helium sales amount to about $550 million, whereas if all the 26 kL of ^{3}He could be separated and sold at $200/L, the total sales would be $5.2 million. Clearly there is little economic incentive for the purveyors of bulk helium to carry out the separation of ^{3}He. Still, a government-contracted operation might intercept a cryogenic stream in the NG purification process, purify the raw helium further, and liquefy it, with due attention to reversibility of the process, because 5 million liters of helium must be liquefied (and then evaporated) to obtain one liter of ^{3}He.

After considering several approaches to extraction of the ^{3}He, including gas centrifuges operating at 4ºK, it seems to me that the “heat flush” phenomenon peculiar to superfluid helium is by far the best way.[2] Soller, et al, achieved a single-stage enrichment factor of 30,000 for ^{3}He from natural helium. Below the lambda point at 2.2 ºK, superfluid helium contains a gas of excitations (“normal fluid”) in the superfluid background. ^{3}He is pinned to the normal fluid and can be driven across the container by a small thermal gradient that essentially creates normal fluid at the warm side and condenses it at the cold side. For a single-effect heat flush, essentially all the ^{3}He could be removed for a cost (including refrigeration of this heat to rejection at room temperature) of some $5-15 per liter STP) of ^{3}He, assuming electrical energy at $0.05/kWh. Since the energy expenditure in a modern commercial plant for producing and delivering liquid helium is about 1 kWh/L of liquid, if this energy investment were not recovered by highly efficient heat exchangers it would contribute[3] ~7150 kWh/L ^{3}He, or ~$357/L ^{3}He (STP) in energy cost alone. Even a modest 90%-efficient heat exchange system to transfer to the helium effluent the sensible heat of cooling the feed stream, and a similar efficiency to use the latent heat of

[2] T. Soller, W.M. Fairbank, and A.D. Crowell, “The Rapid Separation of ^{3}He from ^{4}He by the ‘Heat Flush’ Method,” Phys. Rev., Vol. 91, No. 5, September 1, 1953 (pp. 1058-1060).
[3] [1kWh/L-He liquid][1L-He/(125g/L-He)][4g He/22.4 L (STP)][(5 x 10^6 L He)/(1 L ^{3}He)]

condensation for evaporation of the liquid helium after heat-flush separation of the ^{3}He would reduce the energy expenditure for liquid helium to a tolerable \$36/L ^{3}He gas.

Conclusions

The most urgent step is to increase the price at which U.S. government ^{3}He is delivered to the market, restricting sales, probably, to end users. In addition, government contracts could pay a premium for neutron detectors that do not use ^{3}He—probably in the first instance, boron-lined proportional tube clusters as a direct replacement for ^{3}He proportional counters.

Beyond that, the purchase by the United States of existing titanium tritide canisters would provide several years supply of ^{3}He, and several kL/yr could be obtained from ongoing decay of tritium in the heavy-water moderator of CANDU-style reactors throughout the world.

The first lines of this paper ask the question, "Does it matter?" Assuming a 65 kL/yr demand for ^{3}He and a price escalation to \$200/L, the total sales of ^{3}He would amount to \$13 million per year. This is hardly worth even government consideration, except that some of the applications of ^{3}He are important to national security, to scientific research, and to emerging applications in medicine and technology.

As sketched here, a small but healthy market in ^{3}He would serve society, but care must be taken that the field is not opened to speculators and monopolists, who might drive up the price without assurance of supply and without expanding the availability of ^{3}He. To this end, not only is modeling needed to set the price premium for government purchases of neutron detectors using non-^{3}He technology, but also[4] of the potential games and manipulation by speculators and would-be monopolists in this small but important niche.

** 2140 WORDS. NEED TO CUT TO 1600 AND TO PROVIDE MORE REFERENCES **

[4] R.L. Garwin, "R&D Opportunities and Needs for the Economic Transition," William D. Carey Lecture, (April 30, 2009), at http://www.fas.org/rlg/042209%20R&D_Opportunites_and_Needs2.pdf