Evaluation of Earth's Helium Supply

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Abstract

D-^{3}He is desirable as a fuel mixture for fusion power because it is an advanced fuel, meaning that it produces few high-energy neutrons; and yet with it one still can achieve a sufficient fusion reaction rate for net energy production in the plasma at accessible temperatures. Major obstacles that could prevent the future application of this fuel in powering reactors are the scarcity of helium-3 on earth, the difficulty in confining the plasma long enough to attain the required plasma temperature, and the untested reliability and safety of the technology. In order to address these obstacles, a plan has been proposed to run a number of small field-reversed configuration (FRC) reactors for around 30 years using D-^{3}He. This would test the feasibility of D-^{3}He fusion power and, if successful, encourage pursuit of lunar helium-3 sources. An investigation was conducted to determine whether the terrestrial helium-3 supply is large enough to power a number of small reactors. Current sources and potential future sources of helium-3 were analyzed. The maximum potential fusion power that could be drawn from Earth's helium-3 supply is predicted under various conditions. It is found that, with maximized access to potential sources and proper allocation of these sources, there would be enough helium-3 on Earth to run 10's of 5MW reactors for at least 30 years.

1. Introduction

The utilization of advanced fuels to power fusion would help to reduce certain undesirable effects that are part of the deuterium-tritium (D-T) fusion process. These effects include the production of high-energy neutrons, which can cause activation and damage to surrounding materials and structures; and the low efficiency in converting the energy produced by the fusion reaction into electric energy. Currently, the most practical advanced fuel to use is deuterium-helium-3 (D-^{3}He) because of its ability to yield higher reaction rates in the plasma than other advanced fuels at a given temperature. Despite these advantages of D-^{3}He fuel, certain hindrances have prevented its consideration as a fuel capable of powering the fusion industry of the future. Namely, its requirement of advanced confinement techniques that will contain the plasma long enough to reach a sufficiently high temperature, and the scarcity of helium-3 on Earth, have contributed to widespread doubt in the feasibility of D-^{3}He fuel.

In order to address these concerns, it has been proposed to run a number of small (5MW) field-reversed configuration (FRC) reactors for about 30 years. The FRC is highly compatible with D-^{3}He fuel, mainly due to its high beta value. It is suggested that, if a number of small FRC reactors ran successfully on D-^{3}He fuel for around 30 years, this would demonstrate the feasibility of

D-^{3}He fusion power by revealing the capability of the FRC to effectively contain and heat a D-^{3}He plasma. In addition, such a demonstration, by confirming the plausibility of D-^{3}He fusion power, could help to motivate aggressive pursuit of helium-3 sources on the moon[1] and that this renewed motivation, combined with improved technology for mining lunar helium-3, will allow for future access of this nearby abundant helium-3 source. Access to this source would ultimately make possible the widespread use of D-^{3}He fuel to power fusion.

The first step in achieving this goal is to locate a quantity of helium-3 on Earth large enough to power a number of small reactors for around 30 years. Research was conducted to gain an understanding of the size and availability of the helium-3 supply on Earth. Current sources and potential future sources of helium-3 were analyzed, and are presented here. The maximum potential fusion power that could be drawn from Earth's helium-3 supply is predicted under various conditions.

2. Background

Earth's deficiency of helium-3 is not shared with the universe as a whole. In fact, relative to most elements, helium-3 is quite abundant in the universe. It accounts for .03% of natural helium, which is the second most abundant element in the universe[1]. As shown in Figure 1, this level of abundance is comparable to that of carbon, nitrogen, neon, or silicon.

This sizable concentration of helium-3 in the universe is thought to be similar to primordial conditions[1], and is preserved in stars and gaseous planets. However, moons and rocky planets like Earth do not retain these levels of helium-3 due to processes that occur during their formation. Still, it is common for such bodies to accumulate quantities of helium-3 on their surfaces from cosmic winds. For example, it is estimated that the surface of the moon contains about 10^9 kg, or 7.54×10^{12} L, of ^{3}He that has been deposited there over time by the solar wind[2]. The consistency of the solar wind is 95% free protons and electrons, with the remaining 5% containing various isotopes that are created by nuclear reactions in the sun[3]. In the high energy and gravitational field of the sun, a proton may fuse with a deuterium nucleus to form helium-3, which consequently turns up in the solar wind and is deposited on the surface of the moon. Earth's surface, on the other hand, is prevented from accumulating helium-3 because both its geomagnetic field and atmosphere act as shields to the

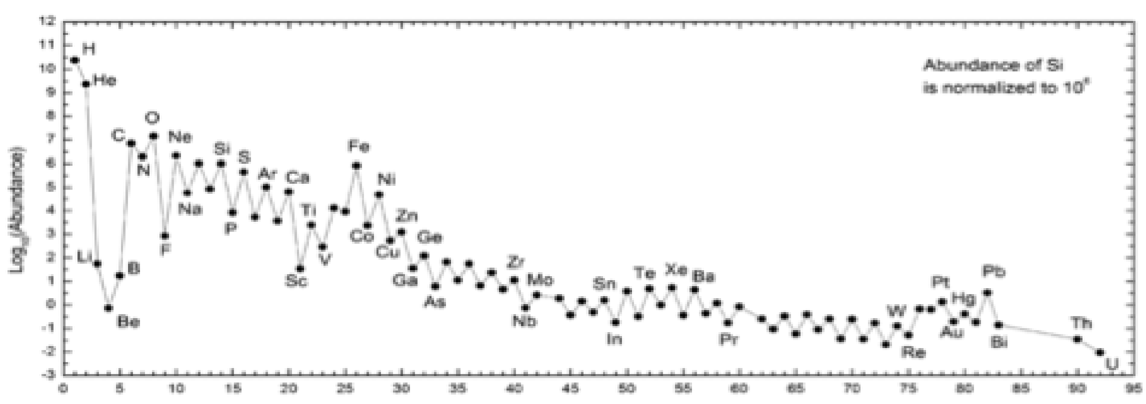

Figure 1: Abundance of various elements in the universe. Helium is the second-most abundant element, with helium-3 constituting .03% of it. This means that helium-3 has a universal abundance equivalent to that of carbon, nitrogen, neon, or silicon.

solar wind. Thus a combination of various planetary traits has prevented Earth from possessing any significant portion of the primordial quantities of helium-3.

This depletion of terrestrial helium-3 is exacerbated by the fact that much of the helium-3 on the earth is not currently accessible. Considerable quantities of the isotope are stored in the atmosphere, oceans, and natural gas wells of the earth. It is estimated that about 4 million kg are distributed throughout the atmosphere, while around 13,260 kg could be found in oceans and natural gas wells[2]. However, since these quantities are dispersed among such large bodies, they exist in very low concentration. Therefore, it would not be very cost-efficient to extract them.

3. Current Helium-3 Sources

As Earth's largest helium-3 sources are thus currently not mined, today the main supply of helium-3 comes from the decay of man-made tritium. Tritium (^3H) is a radioactive isotope of hydrogen that undergoes beta decay with a 12.3-year half-life to form helium-3. Tritium is also a key component of various nuclear weapons. During the Cold War, both the U.S. and Russia produced large quantities of tritium to utilize in their nuclear weapons supplies. In order to maintain these stockpiles of tritium, tritium that had decayed into helium-3 had to periodically be extracted and replaced with newly created tritium. Both countries stored the helium-3 that they extracted and eventually built up a stockpile of it over time.

3a. U.S. Helium-3 Supply In the U.S. tritium production by the irradiation of lithium at the Savannah River Site's K-Reactor began around 1955. The Atomic Energy Commission (AEC) carried out this process, and owned the tritium that was produced. The AEC used the tritium to supply the U.S. nuclear weapons stockpile. In order to maintain the tritium stockpile, the AEC needed to extract helium-3 regularly and replace it with tritium created by the K-Reactor. The extracted helium-3 was then stored in pressurized cylinders at Savannah River Site. During the mid- to late twentieth century, there was very little demand for helium-3, causing a substantial supply to accumulate as the AEC and its successor agencies continued to extract helium-3 regularly from the tritium stockpile.

Although tritium production in the U.S. was halted in 1988 due to problems that arose with the K-reactor, the production of helium-3 was still able to continue. This is because the closing of the reactor coincided with a reduction of the nuclear weapons stockpile, meaning that helium-3 could continue to be extracted from the reduced stockpile of tritium because it could be replaced with recycled tritium from dismantled weapons.

Passed down from the AEC to each subsequent agency that replaced it, the responsibility of the U.S. tritium stockpile and helium-3 production finally fell into the hands of the National Nuclear Security Administration (NNSA) in 2000, and remains a part of this agency's mission today.

The production of tritium was reinstated in 2003 when the DOE authorized the start-up of the Watts Bar Reactor at Tennessee Valley

Authority (TVA). The Watts Bar Reactor continues running today. The reactor irradiates lithium rods, causing helium-4 and tritium to be produced when a neutron combines with a lithium-6 nucleus. Once irradiated, the lithium rods are sent to the Tritium Extraction Facility at Savannah River Site, where the tritium is extracted from the rods and added to the NNSA's stockpile. While the tritium produced by the Watts Bar Reactor does contribute to the tritium stockpile maintained by the NNSA, these contributions are currently limited, requiring the NNSA to continue to rely upon recycled tritium from dismantled weapons to supply its stockpile. However, it is expected that in the future, once the recycled tritium has been exhausted, the production of tritium through the irradiation of lithium will become the main source of helium-3 in the U.S.[4]

Given these supplies of tritium, the NNSA is able to keep a stockpile of such a size that, in order to maintain it, they must extract about 8,000-10,000L/year of ^{3}He[5]. This annual extraction rate accounts for the total production of helium-3 in the United States.

In spite of this constant production rate, the quantity of helium-3 constituting the U.S. supply is not continuously increasing. Instead, it has been decreasing by varying annual decrements since 2001. The negative growth rate of the stockpile is a result of annual sales of helium-3 by the Isotope Program, with customers selected by a specific allocation process. Around 1990, the NNSA engaged the Isotope Program to begin selling helium-3, hoping to recover some of the cost of extracting it. Still, until 2001, demand was very low and so the size of the helium-3 stockpile continued increasing even with sales. Finally, in 2001, helium-3 became highly coveted for its significant role in neutron detection applications, which were regarded as high priority following the terrorist attacks of 9/11. From this point forth, annual demand has far exceeded annual production, leading to a reduction of the helium-3 stockpile. For a summary of the size, additions to, and disbursements from the NNSA helium-3 stockpile since 1990, see Figure 2.

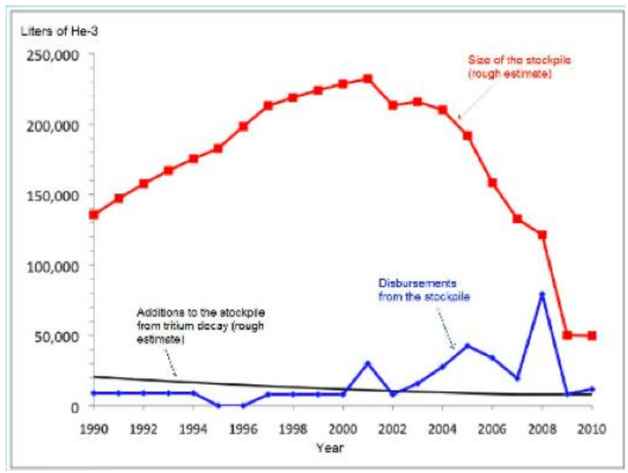

Figure 2: Size, additions to, and disbursements from U.S. helium-3 stockpile each year from 1990-2010. Due to low demand, the stockpile continuously increased in size until 2001. At this point, demand for helium-3 use in neutron detection applications shot up, resulting in a constant decrease in size of the stockpile since 2001.

The imbalance between the limited helium-3 supply and the increasingly larger demand for it did not become apparent to the U.S. government until 2009, at which time it formed a policy committee to regulate the allocation process of helium-3. The committee receives requests from customers for certain quantities of helium-3, which it can then either approve or reject. If a customer's request is rejected, he or she must wait until the next year to re-apply. Meanwhile, if the request is approved, the committee notifies the Isotope Program, which sends the requested amount to Linde Specialty Gases, a major gas company that exclusively possesses the authorization to purify helium-3 by extracting traces of tritium from it. Once the helium-3 is purified, Linde distributes it on behalf of the Isotope Program to the customer, who buys it at a price set by the Isotope Program. This price is currently estimated to be around $600/L for government agencies and $1000/L for commercial users[6].

3b. Russia Helium-3 Supply In addition to the helium-3 created from the U.S. nuclear weapons stockpile, another supply of helium-3 on earth at this time is from the decay of tritium created for Russia's nuclear weapons. Just like the United States, Russia produced large quantities of tritium during the Cold War to supply their nuclear weapons stockpile. They similarly maintained their tritium supplies by periodically extracting helium-3 and replacing it with new tritium, causing a stockpile of helium-3 to accumulate. Information has not yet been obtained regarding the amount of helium-3 currently in Russia's possession, or their annual production rate of the isotope. Congressman Brad Miller, chair of a subcommittee overseeing the helium-3 shortage and Democratic representative from North Carolina, is recorded to have said that the joint production of helium-3 between the U.S. and Russia amounts to 20,000L/year[7]. If this estimate is accurate, it would mean that the helium-3 production rate in Russia is similar to that in the U.S., since it is known that 8-10,000L are produced annually in the U.S. However, while this information regarding the helium-3 made in Russia is uncertain, it is known that they supplied a significant portion of the helium-3 consumed in the U.S. from 1995-2001[8], and exported 25,000L/year to America from 2004-2008[8]. However, in 2008, Russia announced that they would be reserving their helium-3 supply for domestic use only. While the reason behind this action is unknown, it is probable that Russia too is experiencing a shortage of helium-3, whether from dwindling supply, increased demand, both, or another cause.

4. Potential Future Helium-3 Sources

Decaying tritium in the U.S. and Russia is the primary source of helium-3 that is presently accessible. This is obviously a concern because the tritium supplies in each of these countries are diminishing as more and more of the tritium decays into helium-3; and, as the tritium supplies diminish, the annual production rate of helium-3 will decrease. Efforts are being made in the U.S. to address this problem through the operation of the Watts Bar Reactor to produce additional tritium for the stockpile. However, tritium production at the Watts Bar Reactor is still limited, and it is unknown whether it will be able to provide an adequate quantity of tritium to replace extracted helium-3 each year in the future once the

NNSA's stores of recycled tritium from dismantled weapons are used up. Yet, even if the U.S. and Russia could infinitely sustain their present helium-3 production rates, this would barely suffice to power 10 5MW reactors, assuming that all the helium-3 produced was put to this use. In short, additional sources of helium-3 are needed to make feasible the possibility of powering a number of small fusion reactors for about 30 years with terrestrial helium-3. Fortunately, several potential additional sources were uncovered in research and are presented here.

4a. Helium-3 from CANDU Reactors One potential future source of helium-3 on earth is the decay of tritium that has been extracted from Canadian Deuterium Uranium (CANDU) reactors. CANDU reactors are unique in that they use heavy water as a moderator for the nuclear reactions. Thus, when the deuterium in a heavy water molecule absorbs a neutron, tritium is created. Many sites with CANDU reactors extract this tritium from the heavy water in order to reduce the radioactivity of their reactors. The stored tritium eventually decays into helium-3, although so far no site has extracted this helium-3 from their stores of tritium[5,6,9]. The CANDU reactor site with the biggest potential helium-3 supply is Ontario Power Generation (OPG), owned by the province of Ontario. OPG operates 16 CANDU reactors, extracting about 15Mci, or 11,700L, of tritium each year from the heavy water of their reactors[9]. They store this tritium in various Immobilized-Tritium Containers. At this point, OPG is not extracting any helium-3 from their tritium stores, but it is estimated that if they did start this process, it would yield an initial supply of 100,000L ^{3}He, while allowing OPG to produce about 10,000L/year ^{3}He after that[5]. The DOE is currently in discussions with OPG about making their potential supply available by extracting helium-3 from their stores of tritium[9,10].

While it is predicted that OPG possesses the largest potential supply of helium-3, other sites with CANDU reactors around the world also have the potential to provide substantial quantities of helium-3. In addition to Canada, CANDU reactors are used in India, South Korea, China, Pakistan, Argentina, and Romania[5]. India is known to extract tritium from the heavy water of its reactors, but authorities there are unwilling to disclose information about how much tritium they have extracted and what their rate of extraction is[11]. South Korea began extracting tritium from their reactors in 2007 and has extracted about 4kg (30,000L) so far. Since South Korea began extracting its tritium so recently, not enough time has passed to produce significant amounts of helium-3 yet[6]. Information has not yet been obtained regarding whether the additional countries listed previously extract tritium from their CANDU reactors. If they do perform this process, or plan to begin to in the future, these countries could also contribute to Earth's future helium-3 supply.

4b. Naturally Occurring Helium-3 In addition to helium-3 formed from the decay of man-made tritium, naturally occurring helium-3 could constitute a part of the future stockpile on Earth.

Due to the low concentrations of helium-3 in terrestrial sources, the only manner of obtaining natural helium-3 that could possibly be cost-efficient in present times is to extract it from natural helium that has already been separated from natural gas. The DOE is currently considering helium-3 extraction from two reserves that fit this criterion because they contain stores of natural helium that was extracted from natural gas wells. One of these is the National Helium Reserve near Amarillo, Texas. This reserve, containing over 1 trillion liters He, consists of helium that was purchased and compiled by the national government from various surrounding gas reserves in Texas and Kansas. These reserves contained larger than usual quantities of helium due to the accumulation of alpha particles released during the radioactive decay of uranium and thorium ores. The increased concentration of helium in these reserves is what prompted the U.S. government to purchase the helium extracted from them and gather and store it in the National Helium Reserve. While this reserve has so far served only to meet the nation's demand for general helium, the DOE is currently considering starting a program to extract the helium-3 from the helium stored in this reserve. The $^{3}He/^{4}He$ ratio of the gas in this reserve is .2ppm, meaning that total extraction of helium-3 from this reserve would yield about 125,000L[5]. Before extraction can be undertaken, however, the DOE has stated that it must conduct a feasibility study to determine whether extracting this helium-3 would be cost-efficient.

Under similar conditions, the DOE is also considering the extraction of helium-3 from a gas reserve in Wyoming. Recently, a plant was constructed to separate helium from the natural gas in this reserve, a process that began in November 2011. The DOE now contemplates extracting helium-3 from this separated helium, although they will again require a feasibility study before beginning the process of extraction. Although it cannot be known with certainty what quantity of helium-3 this reserve could yield because the maximum quantity of helium has not yet been separated from the natural gas, it is estimated that around 200,000L ^{3}He could ultimately be obtained[5].

4c. Other Potential Helium-3 Sources Through various investigations, the DOE has identified other potential sources of helium-3 that could be utilized for short-term needs, although they are not large enough to contribute significantly to the total stockpile in the long term. For example, the DOE estimates that about 1500L 3He could be recovered from unused equipment in various national laboratories. Similarly, it predicts a yield of 8,000-10,000L of helium-3 every 8-10 years from retired tritium beds at Savannah River Site[5].

In summary, the current stockpile of helium-3 on earth is entirely supplied by tritium that was created by either the United States or Russia to maintain nuclear weapons and has now radioactively decayed into helium-3. Despite a nearly constant annual rate of production of helium-3 as the tritium decays, the stockpile has been steadily decreasing since 2001, when the demand for helium-3 shot up drastically as a result of its role in neutron detection applications. Several potential additional sources of terrestrial helium-3 could serve to increase the total stockpile if accessed and exploited. These sources include tritium extracted from CANDU reactors, natural helium-3 extracted from natural gas reserves, and other miscellaneous sources. See Figure 3 for a summary of Earth's total potential helium-3 supply.

Approximate Current Inventory (L)	Annual Production Rate (L/year)	Current Form (S-separated, NS-mixed)	Location	Source
31,000	8,000-10,000	S	Savannah River Site	Decayed tritium of nuclear weapons stockpile
100,000	10,000	NS, w/ tritium	Ontario Power Generation	Decayed tritium from heavy water reactors
125,000		NS, w/ 4He	Amarillo, Texas	Natural helium gas in earth
200,000		NS, w/ 4He or natural gas	Wyoming	Natural helium gas in earth
1500	8,000-10,000 every 8-10 years	NS	National labs; Savannah River's TEF	Unused equipment and supplies; retired tritium beds
Undisclosed	Undisclosed	NS, w/ tritium	Russia, India, South Korea	Decayed tritium

Figure 3: Summary of potential helium-3 supplies on Earth.

5. Potential Power Yield

In order to be able to gauge the significance of this supply, the maximum potential fusion power that could be drawn from it was calculated under various conditions. In each case, it was assumed that there was access to all the potential helium-3 sources on Earth to their full extent. Also, the annual production rate was maximized to 20,000L/year ^{3}He in each case, based upon the assumption that 10,000L ^{3}He would be contributed annually by both the NNSA and OPG. Finally, it was assumed that the only disbursements from the stockpile would be utilized to power 5MW fusion reactors. Optimal conditions were assumed for each case because the large numbers of variables that factor into the size of Earth's future helium-3 supply render it extremely difficult to predict accurately. Therefore, the most concrete measurement regarding the future supply that can be made is its maximum potential. Also, the measurement of the maximum potential is useful because it allows for the determination of an upper limit of what can be accomplished by utilizing the supply of helium-3 on earth.

In the first case (Figure 4), the initial inventory of helium-3 is determined by the current total supply of helium-3 on Earth.

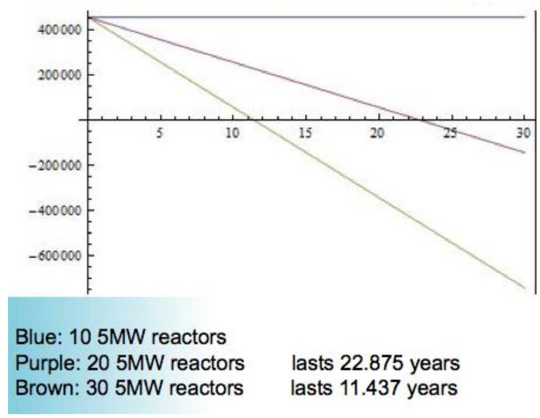

Figure 4: Size of Earth's helium-3 supply (in liters) vs. time (in years since initial time t=0) running 10, 20, and 30 5MW reactors. Here it is assumed that the initial inventory is the current total supply of helium-3 on Earth.

In the second case (Figure 5), the initial inventory is determined by increasing the initial inventory as if 10 years of accumulating the annual production rate of 20,000L/year had passed before starting to run the reactors.

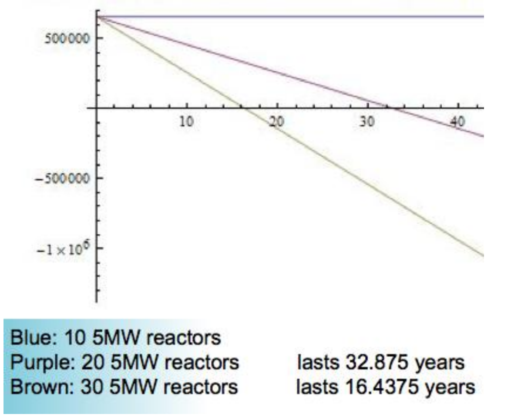

Figure 5: Size of Earth's helium-3 supply (in liters) vs. time (in years since initial time t=0) running 10, 20, and 30 5MW reactors. Here the initial inventory is set to the size it would be if 10 years passed from now until time t=0, when the reactors start running. The value of the initial inventory size is obtained by adding the product of the annual production rate and 10 years (20,000 L/year x 10 years) to the current total supply.

In the third case (Figure 6), the initial inventory is determined by increasing the initial inventory as if 40 years of accumulating the annual production rate had passed before starting to run the reactors.

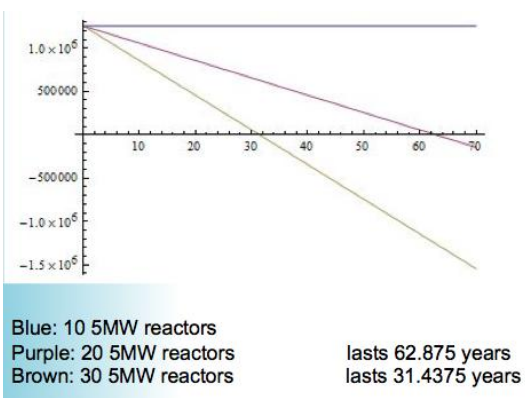

Figure 6: Size of Earth's helium-3 supply (in liters) vs. time (in years since initial time t=0) running 10, 20, and 30 5MW reactors. Here the initial inventory is set to the size it would be if 40 years passed from now until time t=0, when the reactors start running. The value of the initial inventory size is obtained by adding the product of the annual production rate and 40 years (20,000 L/year x 40 years) to the current total supply.

The results shown in the figures suggest that, if access to a majority of the helium-3 sources on Earth is maximized and these sources are allocated properly, the ability to power 10, 20, or 30 5MW reactors for anywhere around 10-60 years is definitely feasible. The realization of this ability largely depends on what degree of access to Earth's various potential helium-3 sources is available in the future. Efforts are currently being made to maximize access to these supplies. The DOE is considering alternatives to replace helium-3 in various applications so as to reduce annual disbursements from the NNSA stockpile. For example, it is considering the use of lithium-6 and boron-10 instead of helium-3 in neutron detection applications[5]. Additionally, the DOE is also in discussions with OPG about making its potential supply available. Finally, the DOE plans to start irradiating lithium rods to produce tritium at two additional reactors operated by the TVA. This would result in a larger tritium stockpile, leading to a greater annual production rate of helium-3.

Conclusion

It is found that sizable supplies of helium-3 exist on Earth. In addition to the sources that are currently utilized (the decay of the tritium used in the nuclear weapons stockpiles of both the United States and Russia), several potential additional sources were found. These sources include the decay of tritium extracted from CANDU reactors, naturally occurring helium-3 separated from natural gas, and other miscellaneous sources.

While the exact size of the helium-3 supply that will be available in the future is unpredictable because of political and economical reasons, the maximum potential power that could be drawn from the future supply was calculated. These calculations support the plausibility of fueling a number of small FRC reactors with $D\text{-}^3He$ fuel for 30 years. This ability would make it possible to carry out the proposed plan that would demonstrate the feasibility of $D\text{-}^3He$ fuel and encourage the pursuit of abundant lunar ^3He sources.

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