Nuclear power without radioactive waste? The lunar helium-3 perspective

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^{3}He mining on the Moon has recently received much interest and was proposed as an incentive for lunar exploration, with ^{3}He as the perfect fuel for nuclear fusion energy without radioactive waste. The Earth has no significant ^{3}He resource. However, the lunar regolith, the upper few meters of loose material on the Moon, appears to contain about 20 ppb of ^{3}He implemented by solar wind over billions of years. The value of ^{3}He can be estimated at around 1 million US$/kg, based on energy content and comparison with nuclear fission reactors and zero-emission coal plants. The corresponding ore value then is 20 US$/t. Both grade and value-per-tonnage data are comparable to marginal diamond mining on Earth, but the specific economics of Moon mining will greatly depend on a drastic reduction of the currently prohibitive transport costs, as well as on support from other space activities.

Kernkraft ohne radioaktiven Abfall? Der Mond als Eldorado für Bergbau auf Helium-3

Bei der Mond-Exploration in den kommenden Jahren wird der mögliche Tagebau auf ^{3}He eine wichtige Rolle spielen. Die ^{3}He-Ressourcen der Erde sind nur unbedeutend, und künftige Fusions-Kraftwerke, die auf Kernreaktionen ohne hohen Neutronenfluss basieren werden, benötigen extraterrestrisches ^{3}He. Hierzu bieten die oberen Meter von feinstkörnigem Lockermaterial auf dem Mond (Regolith) eine interessante Ressource, wo durch den Sonnenwind über mehrere Milliarden Jahre in einigen Bereichen rund 20 ppb ^{3}He implementiert wurden. Der Wert von ^{3}He kann durch Vergleich des Energieinhalts mit Uran und Kohle, den in einigen Jahrzehnten voraussichtlich wichtigsten Energieträgern, auf rund 1 Mio. US-$/kg geschätzt werden, wobei die Investitions- und Produktionskosten von Uran-Kernkraftwerken, Kohle-Kraftwerken mit Null-Emission (CO_2-Sequestrierung) und ^{3}He-Fusions-Kraftwerken in ähnlicher Größenordnung gesehen werden. Sowohl der Rohstoff-Wert von ^{3}He als auch der Gehalt im Mond-Regolith sind vergleichbar mit marginalem Diamant-Bergbau auf der Erde. Entsprechend kann Mond-Bergbau nur durch drastische Senkung der gegenwärtig extrem hohen Transportkosten wirtschaftlich werden, was physikalisch nicht unmöglich ist.

1 World energy demand

Energy is a basic resource, securing in today's world prosperity, safety and independence. The energy market is a multi billion US$ market with enormous growth rates. The dependence of the industrialized world with its information- and communication-based societies on electric power makes research for energy efficient machinery and the search for new energy resources a prime goal of every government. World population growth and the emergent economies of the developing countries fuel a world demand for electrical power which is likely to double by 2030. The current world electricity production of $15,000 \cdot 10^9$ kWh is comprised of two-thirds burning fossil fuels. Other energy production mechanisms, like nuclear fission, are considered problematic, due to the fact that reactors and the long-term storage of radioactive waste are widely perceived as a safety problem. Renewable energy, although highly favourable from an environmental point of view, is unlikely to close the energy gap in the next decades. Nuclear fusion is therefore hoped to become an alternative to the major current energy conversion technologies, which are all variably detrimental to the environment.

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2 Fusion energy and its prospects

The basic understanding of fusion energy is essentially established. The technical problems towards large-scale electricity production, however, require tremendous engineering efforts, as can be seen in the recent launch of the 10-billion-EUR International Thermonuclear Experimental Reactor (ITER) project with its 500-MW experimental plant in Cadarache in southern France. The ITER program will focus on the so-called first-generation fusion fuels deuterium ($D = {}^2H$) and tritium ($T = {}^3H$), which generate energy through the reaction:

$${}^2H + {}^3H = {}^4He \ (3.5 \ \text{MeV}) + {}^0n \ (14.1 \ \text{MeV}).$$
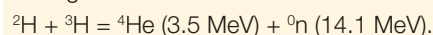
This first-generation fusion fuel reaction has the advantage of burning most easily but comes with serious drawbacks:

- Tritium is toxic, radioactive ($T_{1/2}$ = 12.3 a), and is a key ingredient for thermonuclear weapons;
- Tritium must be produced artificially in nuclear reactors via the reaction $^6Li \ (n, \ \alpha)^3H$; the currently available amounts of T are sufficient for experimental use only; the price of large-scale tritium breeding is estimated at 10,000 to 100,000 US$/g [10];
- Most of the fusion energy is carried by high-energy neutrons, which requires a secondary heat cycle, as do fossil fuel plants and nuclear fission reactors. This requirement limits the energy conversion efficiency to about 40 %;
- Most importantly, the high-energy neutron flux physically damages the confining structures of D-T fusion reactors, which is a

central issue not only in terms of financial replacement costs but also in terms of waste management. The walls become highly radioactive due to the neutron-induced nuclear reactions and must be disposed of as high-level radioactive waste. The D-T reaction actually releases four times as many neutrons per unit of energy than a fission reactor [5].

The above-mentioned drawbacks make clear that first-generation fusion technology is unlikely to become a widely accepted solution to the energy problems of the world.

The second-generation D-^{3}He fusion fuel cycle uses no radioactive fuel:

^{2}H + ^{3}He = ^{1}H (14.7 MeV) + ^{4}He (3.7 MeV).
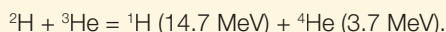
One of the main advantages of the second-generation fuel cycle is that the radiation damage to fusion chamber structures is greatly reduced, allowing these components to last the full lifetime of the power plant. This fuel cycle produces little or no long-lived radioactivity, thus reducing the expense of decommissioning a plant when its working life is over. A large fraction of the fusion energy is released in the form of charged particles, and thus would allow direct conversion to electricity at efficiencies of 70 % or higher. This is roughly twice what the first generation fuels will attain with thermal conversion. Nevertheless, the D-rich plasma will also produce a minor amount of neutrons due to D-D fusion:

^{2}H + ^{2}H = ^{0}n (2.5 MeV) + ^{3}He (0.8 MeV) =

^{1}He (3 MeV) + ^{3}H (1 MeV).
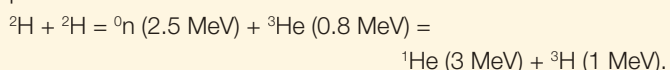
The main disadvantage of the second generation fuel cycle is that there is the requirement of four to five times higher temperatures (400 million degrees) and better confinement conditions compared to the first-generation fuels.

The D-^{3}He energy conversion has the promise of least environmental impact and of best safety of all high-density energy technologies. The burning of 1 kg of ^{3}He with D will release 600,000 GJ, i.e. about 170 million kWh. The total current world electricity consumption then corresponds to the energy content of 100 tonnes of ^{3}He/year.

The so-called third-generation fusion uses pure ^{3}He:

^{3}He +^{3}He = 2 ^{1}H + ^{4}He (total 12.9 MeV).
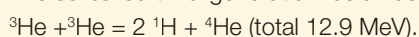
This reaction produces no neutrons, and neither the fuel nor the reaction products are radioactive. This apparently perfect nuclear reaction comes at the cost of even higher plasma temperatures, currently far beyond technical feasibility.

Once the technological hurdles in the second-generation fusion process are taken, a major problem for the use of the ^{3}He fusion technology will be the scarcity of ^{3}He on Earth.

3　Helium-3 on Earth

Most of the helium on the near-surface Earth is from uranium and thorium decay. Therefore, the ^{3}He/^{4}He ratio is very low, and depends mostly on dilution of primordial (dating back to the formation of the Earth at 4.56 Ga) helium by radiogenic ^{4}He. The continental crust with elevated U-Th concentration has the lowest ^{3}He/^{4}He ratios down to $2 \cdot 10^{-8}$ (atomic), while mantle-derived helium has much higher ^{3}He/^{4}He ratios up to $100 \cdot 10^{-6}$ in so-called mantle plumes which tap the deepest mantle. It appears that there is a large reservoir of primordial helium (with possibly ^{3}He/^{4}He = $1.7 \cdot 10^{-4}$, as measured by the Galileo probe on Jupiter) in the 300-km-thick DD" layer at the interface of the liquid outer core and the lower mantle, where chondritic material from the earliest accretion history of the Earth may have survived, isolated from the convecting mantle [8]. This reservoir is estimated to hold about 2 to 3 Gt of ^{3}He, but is inaccessible at 300-km depth. The atmosphere of the Earth has about 5.2 ppm He (by volume) with a ^{3}He/^{4}He atomic ratio of $1.4 \cdot 10^{-6}$, which gives a total amount of about 4000 t ^{3}He. This helium represents a steady-state between the outgassing

of helium from the solid Earth plus extraterrestrial sources, and the escape of helium to space with a half life of about one million years. However, the industrial processing of major portions of the atmosphere for helium recovery is difficult to realize.

The current helium production of about 160 million m^3/a is from natural gas fields which have variable helium abundance with essentially crustal ^{3}He/^{4}He ratios. The yearly ^{3}He content in this amount of helium is about 7 kg ^{3}He, which can currently be purchased at about 700 to 1000 US$/g.

^{3}He also forms from the decay of tritium ($T_{1/2}$ 12.3 a), which has been produced in nuclear fission reactors and which is used in thermonuclear weapons. It is estimated that the US weapons stock generates about 15 kg ^{3}He/a, and that 100 to 300 kg ^{3}He are stockpiled. Tritium can also be produced artificially in both fission and fusion reactors by the absorption of thermal neutrons in lithium, via the reaction ^{6}Li(n,α)^{3}H, and then decays naturally to ^{3}He. The production cost, however, is estimated at about 100,000 US$/g T, but may be as low as about 300 US$/g T in a D-T nuclear fusion breeder [10], which would change the economics of the ^{3}He market.

4　Extra-terrestrial helium resources

In terms of cosmic abundance, helium is the second most abundant element. Many features of the universal abundance curve for chemical elements can qualitatively be understood through a knowledge of their nuclear properties. Isotope fractionation by physical or chemical processes is responsible for the fact that measurements of element abundances in the universe reveal different values of isotope ratios. The currently available best data which give a protosolar ^{3}He/^{4}He value of $1.66 \pm 0.06 \cdot 10^{-4}$ [6] are from the Galileo Probe Mass Spectrometer on Jupiter's atmosphere.

While the outer planets are too distant to be of interest for near-term space exploration plans, our Sun itself consists of about one-quarter helium, with about 10^{26} kg ^{3}He, a larger mass than the entire Earth. Although the Sun's outermost region, the corona, is strongly attracted by solar gravity, heat conduction is so high that the corona expands supersonically into interstellar space, thus leading to a steady outflow of solar material known as the solar wind. The solar wind, consisting largely of protons and helium ions, has an average speed of 400 km/s and is highly variable. The isotopic helium composition of the solar wind is affected by fusion processes in the Sun, and by isotopic fractionation processes both inside the Sun and during travel. Its ^{3}He/^{4}He ratio is about $4.5 \cdot 10^{-4}$, i.e. about 320 times greater than in the Earth's atmosphere [3, 9]. While the terrestrial magnetic field shields the Earth from the solar wind flow, the Moon, with no magnetic field, is constantly exposed to this particle stream on its sunlit side since its formation 4.5 Ga ago. When the solar wind ions hit the upper surface layer of the Moon they strike a blanket of broken-up material known as the regolith, consisting mainly of very fine-grained particles of less than 1 mm in diameter (Figure 1). The solar wind ions have a limited penetration depth of only a few μm in the lunar regolith, due to their limited energy. Because the lunar regolith has been produced by the repeated impact of high velocity bodies over more than 4 billion years, a process known as "impact gardening" has continuously overturned the soil to several meter depth, thereby burying solar-wind enriched material and bringing new material to the surface. Solar wind implanted material can be released by simply heating the regolith in a vacuum furnace, as is routinely done in the investigation of lunar sample materials.

The abundance of ^{3}He in the Moon regolith is dependent on the surface age (maturity), the solar wind flux and the soil chemistry. EBERHARDT et al. (1970) could show that ilmenite fractions from Apollo 11 and Apollo 17 mare regoliths are enriched in He [2]. Figure 2 shows the relationship of the He contents of the regolith and their Ti content for samples of mare and highland regolith.

Fig. 1: Astronaut and geologist Dr. Harrison Schmitt sampling the Moon regolith during the Apollo 17 mission in the valley of Taurus-Littrow on 14 December 1972. (NASA photograph AS17 134 20425).
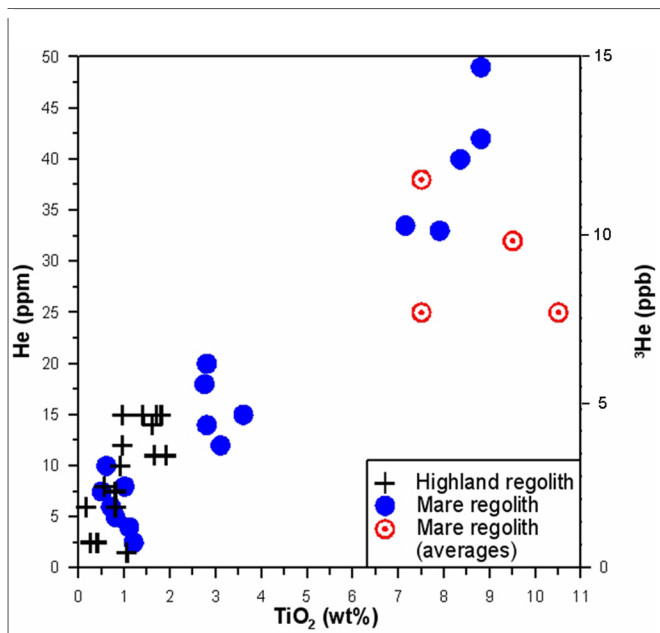

Fig. 2: Relationship between He (and equivalent ^{3}He) and TiO_2 content of lunar regolith samples (data from Apollo and Luna missions, compiled in [1]. The average ^{3}He content of the regolith from Mare Tranquillitatis at > 7.5 wt.-% TiO_2 (sampled at the Apollo 11 landing site) is around 15 ppb, but losses during sampling, transport and laboratory handling on Earth are estimated at around 40 %, which gives an approximate in-situ grade of 20 ppb ^{3}He.

Highland regolith samples are all low in He and Ti content. Mare regolith is split into a group of low He and Ti, and a group of high He and Ti content. Figure 2 shows a broad correlation of He with Ti content, but there is considerable scatter at the high end. Due to the various factors which influence the absorption of He in the regolith, a simple linear relation between TiO_2 content and He content cannot be expected. While only a few mare have been sampled so far, the determination of the TiO_2 content using remote sensing information remains, at the moment, the only viable method to investigate the regional distribution of ^{3}He [4].

It is obvious that the small quantities of ^{3}He trapped in regolith particles would require thermal processing of large amounts of lunar regolith, in order to obtain useful amounts of the small fraction that is ^{3}He. To restrict mining operations to as small an area as possible, mining to a maximum possible depth must be achieved. The current consensus is that the regolith is generally about 4- to 5-m thick in the mare areas. The largest uncertainty in the estimates of the total lunar abundance of ^{3}He arises from the lack of knowledge of its distribution with depth below the upper meter or two. The lunar regolith was sampled down to a 3-m depth during the Apollo 15 mission and the abundance of solar helium was not observed to change significantly with depth, although the measured ^{3}He concentrations at the Apollo 15 location were 1 to 5 ppb only. Part of the low ^{3}He abundance is probably due to losses during sampling and handling, and the current best estimate for the undisturbed ^{3}He concentration in the high-Ti basaltic lunar mare regolith at a grain size of < 200 µm is 20 ppb [7]. This grade estimate needs confirmation by much more systematic sampling before a serious grade-tonnage model can be produced.

5   Preliminary economic geology of Moon-derived helium-3

The question of whether lunar ^{3}He can be a usable energy source on the Earth in economic terms boils down to the question of what will the cost be of lunar ^{3}He fuel compared to other energy sources. The cost of energy in a free market economy is determined by supply and demand and is usually investigated by standard economic analysis. In recent years the question has been put forward as to whether economic measures, such as price or cost, can accurately capture all the relevant features of an energy supply process. The indirect cost of energy production from fossil fuels is currently the focus of political discussions in light of increasing atmospheric levels of greenhouse gases and possible climate change. There is also an increasing public awareness of the volatility of the supply chain of oil and gas, which together have a market share of 60 % in total world energy production, of which 70 % of all conventional reserves and resources are in the Middle East and the former USSR. In addition, a fall in global annual oil production after about 2020, when the "depletion mid-point" (peak oil production) is reached, can be reliably forecasted. This situation is different for coal and uranium reserves, which are much more widely scattered geographically, have much longer lasting resources, and are traded in a largely free commodity market. We will estimate the economic potential of ^{3}He in comparison to coal and uranium, the two major high-density energy resources of the 21st century.

^{3}He fusion:

The energy content of 1 kg ^{3}He when fused with D is about 600,000 GJ. A 1000-megawatt electric fusion D-^{3}He power plant would require about 100 kg of ^{3}He annually. It is evident that the terrestrial ^{3}He resource will be enough for the technical development of the helium fusion technology, but commercial energy production will require non-terrestrial ^{3}He (or artificially bred ^{3}He, see above).

The energy content can be used to evaluate the upper price limit of ^{3}He for large-scale use in competition with nuclear fission and

coal combustion. The investment into the three variants of power plants (fusion, fission, clean coal combustion with zero CO_2 output, i.e. CO_2 capture and storage) is estimated to be at the same magnitude, i.e. several billions of US$.

Nuclear fission:
One kg enriched U (3.5 % ^{235}U), as derived from 7 kg natural uranium, has an energy content of 3900 GJ, of which about 1300 GJ (equal to 360,000 kWh) can be transformed to electricity, at a 33 % thermal efficiency. The current price for 1 kg enriched U is about 1630 US$. The equivalent price for the effective energy content in ^{3}He is then about 750,000 US$/kg ^{3}He.

Coal combustion:
One tonne of steam coal has an energy content of about $20 \cdot 10^6$ BTU (British Thermal Unit), which corresponds to 21 GJ, and is reduced to 7 GJ by the same thermal efficiency as in fission power plants. The price of steam coal is about 35 US$/t, which then gives an equivalent price for the energy in ^{3}He of about 3 million US$/kg ^{3}He.

These rough calculations show that the market price for ^{3}He can be assumed to be on the order of 1 mill US$/kg. The grade of the lunar regolith is estimated at 20 ppb ^{3}He, and the extent of the mineable orebody, i.e. the upper 3 m of the lunar mare soil as a conservative estimate, seems to be very large. Remote sensing and elemental mapping data of the Moon define a most promising target area of 84,000 km^2 in the northeastern part of the > 4 Ga-old basaltic impact basin of Mare Tranquillitatis on the lunar near-side, which has > 7.5 wt.-% TiO_2 and relatively low crater density [1] (Figure 3). These 84,000 km^2 then possibly hold a tonnage of 428 Gt at 20 ppb ^{3}He (density 1.7 g/cm^3), i.e. 8500 t ^{3}He, of which probably 50 % would be mineable by a mobile excavation-processing unit. Bucket-wheel or large-width cutting-drum extraction (10 Mt/a), dry cyclone/electrostatic separation, volatile release at 800 °C, and cryogenic ^{3}He separation would rely on well established terrestrial mining and processing techniques, although on-site experiments will probably be required to overcome all kinds of technical problems, of which dust will be a significant one. A 100 kg ^{3}He production unit then would mine a surface area of about 2 km^2 annually, which could feed a 1000 MW fusion plant on Earth [7, 11]. The same ^{3}He extraction process would sustain a by-production of hydrogen (600 t) and
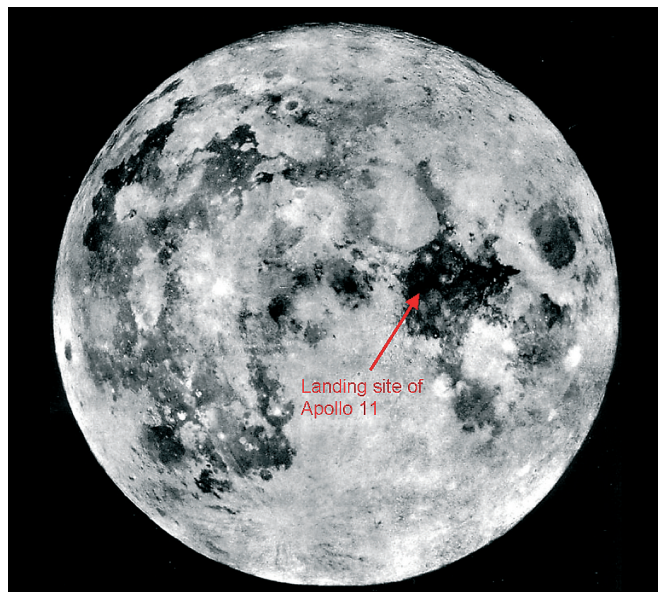

Fig. 3: Color difference photograph of the near-side of the Moon, showing the approx. 300,000-km^2-large Mare Tranquillitatis basin (black, with landing site of Apollo 11), consisting of high-Ti lava flows from a > 4 Ga-old impact. The eastern part of this mare could be the first site of lunar ^{3}He mining. However, the only regolith samples currently available are from near the Apollo 11 landing site. The image was produced by subtracting a photograph taken at a 310-nm (UV) from one taken at a 610-nm (orange) wavelength (Whitaker, E.A., in [1]).

water (300 t) from the hydrogen-mineral interaction during the high-temperature volatile-release step.

The extremely low grade of the lunar ^{3}He ore can be compared to terrestrial diamond ore deposits, which also have grades in the ppb range (commonly expressed as carat per hundred tonnes, with 1 ct = 0.2 g), and commodity values on the order of 1 million US$/kg raw diamonds produced. Such mines, mostly open pit operations, have very variable in-situ ore tonnage values, which mainly range from 10 to 200 US$/t (Figure 4). The lunar surface
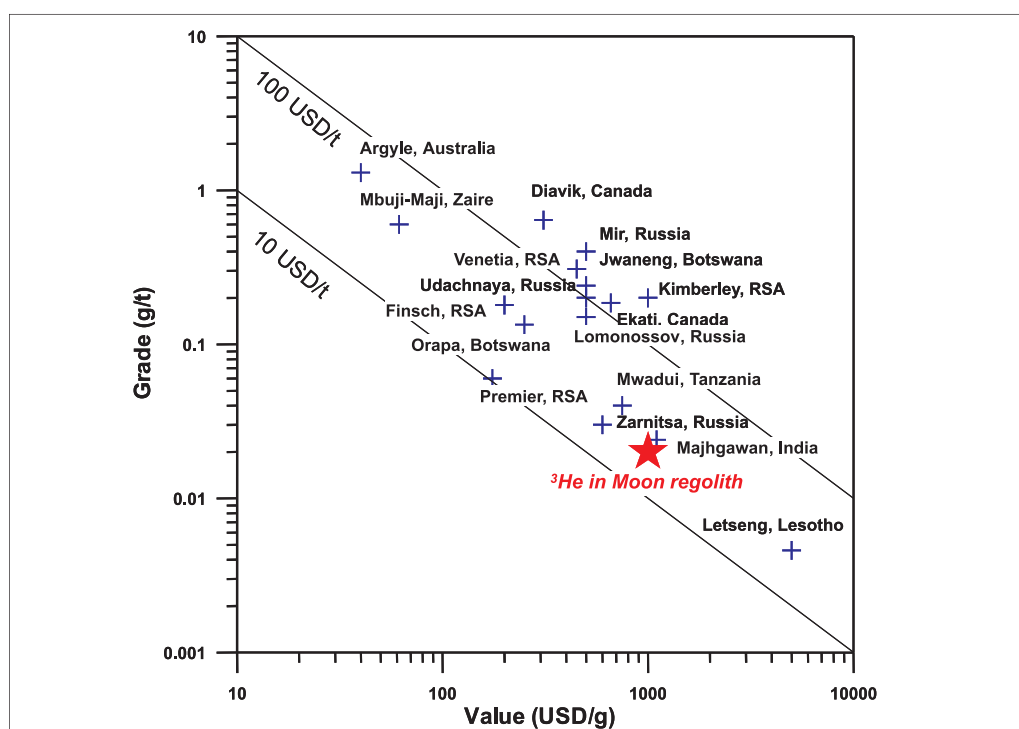

Fig. 4:
Comparison of grade and value of ^{3}He in a Moon regolith to grade and stone value of major hard-rock diamond mines on Earth. In-situ ore value of Moon a regolith is at the lower margin of terrestrial diamond ore, which ranges from 10 to 200 US$/t.

mining operation, with an ore value of about 20 US\$/t, would be at the lower limit of this spectrum, i.e. clearly uneconomic given the distant and hostile, and therefore expensive, environment of the Moon. An all-private approach by international investors is therefore not to be expected. However, governments with a long-term perspective may be interested, as China has already announced interest in prospecting for lunar ^{3}He.

6   Conclusions

Conservation and conversion efficiency alone will not meet the rapidly expanding global energy demand from the many emerging economies on Earth. Whether global warming or cooling will occur, more electricity and more energy in general will be required. Bold technological projects are needed, of which space exploration and fusion energy are in the forefront. Of course, both the vision of lunar mining and nuclear energy without radioactive waste are driven by emotion (and interest of the space industry), beyond current technological possibilities, but not completely without reason. The lunar exploration by six Apollo landings in 1969 to 1972 is already 35 years ago, and was based on the now historical message of John F. Kennedy to the Congress in 1961, rooted in the Cold War and the 1957 Sputnik launch of the USSR: "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to Earth". In January 2004, President George Bush challenged NASA to once again "explore space and extend a human presence across our solar system". Other nations have voiced similar objectives, and the American astronauts are likely to be joined by Russian cosmonauts, Chinese taikonauts, and European and other solar-system travellers. This renaissance of manned space exploration will focus more on extraterrestrial economic benefits, and energy resources will be a major concern.

The deployment of heavy mining equipment on the Moon is currently not feasible, due to the prohibitive transport cost, which is about 60,000 US\$/kg. However, much can be done to drastically lower this cost until the limits of physics are reached which are set at the gravitational potential energy to lift anything from the Earth to the Moon, corresponding to the kinetic energy at the escape velocity on Earth. This theoretical limit is only at 63 MJ/kg (or 17 kWh/kg), i.e. about 1 US\$/kg.

The ^{3}He fusion energy perspective is currently more a carrot for the public in the lobbying for governmental space budgets, than a real near-term option. The economic development of fusion energy is not around the corner, and the current focus on D-T fusion research is unlikely to provide the clean and cheap energy which is desired and advertised. The traditional comment on this field is that commercial fusion power is ten years away – and has been so since the middle of the past century when the basic physics of the D-^{3}He reaction was established [12]. ^{3}He appears to be the perfect fusion fuel, but there are enormous technical problems in both fusion engineering and economic ^{3}He mining, besides the legal and political issues.

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