The College of Engineering
University of Wisconsin-Madison

ABSTRACTS SUBMITTED TO THE SECOND WISCONSIN SYMPOSIUM ON ^{3}HE AND FUSION POWER, 19–21 JULY 1993, MADISON WI

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Technical Report

WCSAR

Wisconsin Center for
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various authors

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Current Speaker List for the
Second Wisconsin Symposium on Helium-3 and Fusion Power

July 14, 1993

SPEAKER	ORGANIZATION	TITLE
H.H. Schmitt	Apollo 17 Astronaut and Former US Senator	Political Implications of D/He-3 Fusion
S. Klug	US Congressman	Pres. Clinton's Energy Program
C.G. Bathke	LANL	Parametric Analysis of the ARIES-III D/He-3 Tokamak Reactor
R.W. Bussard	EMC2 Corporation	Inertial-Electrostatic Fusion from D to 3He: A Practical Strategy for Fusion Development
E.N. Cameron	Univ. of Wisconsin	Further Evaluation of the Helium Potential of Mare Tranquillitatis
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B. Coppi	MIT	Near-Term Experiments on D-He3 Burning
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J.M. Dawson	UCLA	Non-Energy Applications for Fusion
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M.B. Duke	NASA	Concepts for Industry Involvement in Lunar Exploration
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G.A. Emmert	Univ. of Wisconsin	Potential for D-3He Experiments in ITER
I.N. Golovin	Kurchatov Inst., Moscow	About the Concept of Utmost Clean and Beneficial D-3He Reactor
K.R. Harris	Univ. of Wisconsin	Remote Sensing of Lunar 3He
L.A. Haskin	Washington U.	By-Products of Lunar He-3 Mining
J.S. Herring	EG&G Idaho	Safety Analysis of the ARIES-III D-3He Tokamak Reactor Design
A.L. Hoffman	Univ. of Washington	Next Step in FRC Development
J.L. Jordan	Lamar U.	Characterizing the Lunar 3He Reservoir
W. Kernbichler	Technische Universitat Graz	Synchrotron Radiation from High-Temperature Plasmas
H.Y. Khater	Univ. of Wisconsin	Safety Characteristics of D-3He Fusion Reactors
E.B. Kiker	Army Space Institute	U.S. Army Perspectives on Lunar Resource Recovery and Utilization
N.A. Krall	Krall Associates	Physics Issues for Large Orbit Fusion Schemes
G.L. Kulcinski	Univ. of Wisconsin	History and Overview
G.H. Miley	Univ. of Illinois	Comments on D-3He IEC Experiments and Reactor Concepts
H. Momota	Nat'l. Inst. Fusion Sci, Nagoya	Attractive Characteristics of D-3He Fueled FRC Reactor
L. Peoples	Madison Gas and Electric	Utility Perspective on Clean Nuclear Energy
L.J. Perkins	LLNL	Prospects for Novel Thermonuclear and Non-Thermonuclear Fusion
V.I. Pistunovich	Kurchatov Inst., Moscow	D/He-3, Second-Stability Tokamak Reactor Design
N. Rostoker	UC--Irvine	Self-Colliders for D-He3 Fusion
D.D. Ryutov	Budker Inst., Novosibirsk	D-3He Mirror Reactors
J.F. Santarius	Univ. of Wisconsin	Magnetic Fusion Propulsion: Opening the Solar-System Frontier
M.E. Sawan	Univ. of Wisconsin	Assessment of First Wall Lifetime in D-3He and D-T Reactors with Impact on Reactor Availability
J. Sved	Deutsche Aerospace--ERNO	Perspective on He-3 and Power from Space
I.N. Sviatoslavsky	Univ. of Wisconsin	Coaxing He3 from Lunar Regolith: Processes and Challenges
D.K. Sze	ANL	Engineering Design of ARIES-III
L.A. Taylor	Univ. of Tennessee	Evidence for Abundances of Helium-3 on the Moon
H.E. Thompson	Univ. of Wisconsin	Cost of 3He from the Moon
Y. Tomita	Nat'l. Inst. Fusion Sci, Nagoya	Direct Energy Conversion System for D-3He Fusion
R.P. Whitten	NASA	NASA Perspective on Lunar Helium-3 Mining
W.R. Wilkes	EG&G Mound	Potential 3He Resources for D-3He Fusion Development
L.J. Wittenberg	Univ. of Wisconsin	Non-Lunar He-3 Resources

PARAMETRIC ANALYSIS OF THE ARIES-III D-^{3}He TOKAMAK REACTOR†

C. G. Bathke, K. A. Werley, R. L. Miller, and R. A. Krakowski, Los Alamos National Laboratory, Los Alamos, NM 87545; J. F. Santarius, University of Wisconsin, 1500 Johnson Dr., Madison, WI 53706; and the ARIES Research Team - - The recently completed, multi-institutional ARIES project investigated the physics, technology, safety, and economic issues of steady-state tokamak reactors with a series of conceptual designs[1–3] that varies the degree of assumed technology and physics advances. Of these designs, only ARIES-III[2] uses D-^{3}He fuel, which requires significant advances both in engineering and physics to take advantage of reduced neutron production from the lunar-based ^{3}He fuel. The technological advances invoked include: a) high-efficiency (η_{CD} = 0.68), energetic (3-6 MeV) neutral beams for current drive at the high plasma ion temperature (55 keV) necessitated by plasma power balance; and b) advanced, high current-density (40 MA/m^2, averaged over TF coil) superconducting coils that minimize the TF-coil mass and cost. Economics dictate operation in a high-beta ($\beta_\phi = 0.24$), high-safety-factor ($q_0 = 1.95$, $q_{edge} = 6.85$) second-stability regime to reduce the magnetic field ($B_{\phi 0} = 7.6$ T) and the fraction of the plasma power radiated ($f_{rad} = 0.72$) and to reduce the plasma current ($I_\phi = 29.9$ MA) and the current-drive power ($P_{CD} = 172$ MW), respectively. The plasma density and temperature profiles are optimized to minimize bootstrap-current "overdrive" (25%), with the externally driven current being 7.5 MA. Furthermore, a large energy-confinement-time enhancement factor $H = 7.2$ over the ITER-89P scaling is required. Low neutron production levels permit the use of a low-activation, minimum-volume *HT*-9 shield (a tritium breeding blanket is unnecessary) that assures a favorable safety rating (and associated cost credits). The ARIES-III design point was increased in size (major radius $R_T = 7.5$ m and minor radius $a_p = 2.5$ m) relative to the cost-of-electricity (COE) optimum to reduce further the (DD, DT) neutron wall loading (peak $I_w = 0.1$ MW/m^2). Sensitivities about the COE optimum are also presented that illustrate the limited design window available to D-^{3}He tokamak reactors. A comparison of all ARIES designs[1–3] and a first-stability-regime variant of ARIES-III is made on a common costing basis[3] with documentation of physics and technology assumptions.

† Work supported by the US DOE, Office of Fusion Energy

[1] F. Najmabadi, et al., "The ARIES-I Tokamak Reactor Study," University of California Los Angles report UCLA-PPG-1323 (1991).

[2] F. Najmabadi, et al., "The ARIES-III D-^{3}He Tokamak Reactor Study," University of California Los Angles report UCLA-PPG-1384 (to be published).

[3] F. Najmabadi, et al., "The ARIES-II and -IV Second Stability Tokamak Reactors," University of California Los Angles report UCLA-PPG-1461 (to be published).

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Inertial-Electrostatic-Fusion From D to ^{3}He: A Practical Strategy for Fusion Development

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Since 1985, considerable study has been made of the unique Polywell™ concept[1] for inertial-electrostatic-fusion (IEF). This confines ions in a net negative plasma formed from by injection of energetic electrons into a special quasi-spherical, polyhedral B field configuration which traps the electrons; called the EXL (Electron ACCELeration) concept. Unlike earlier approaches that used grids to establish particle accelerating potentials, it has no grids and avoids the collisional losses that limited these. The ions and electrons in EXL systems are never in LTE and never Maxwellian. The device operates as a metastable, driven, non-neutral, spherically-focussing fusion reaction system in which the ion reaction energies are narrowly limited to their kinetic energy at the central core. And, the fusion products can not react with in-situ fuels; they will be exhausted into the external vacuum system, where they can be recovered, reinjected or stored for later application.

No significant physics or engineering obstacles have yet been found. First and second order critical physics issues have been identified and analyzed, and complex computer codes have been developed for particle and potential distributions (EIXL code) and for power balance (PBAL code) in EXL reactors. A host of power balance studies have been made with these codes, over a range of realistically-attainable physics conditions, and a wide variety of potential fusion fuels. These included DT, DD (alone), DD 1/2 and full-catalyzed by ^{3}He (called DDcatA and -catB cycles), D^{3}He (50:50 mix; exogenous ^{3}He), ^{3}He^{3}e, ^{6}Li^{6}Li (through p/^{3}He catalytic chain) and p^{11}B. All of these fuels were found able to run with net power in EXL systems with relatively low-technology engineering parameters. The studies showed that EXL devices of approximately 2.5-4.5 m radius can be made to yield net power on DD, with B fields of 10-15 kG or so, and electron drive voltages of 50-70 keV. Higher power or gain can be achieved by reinjection of the ^{3}He produced in one branch of the DD reaction (DDcatA). This increases the energy per DD reaction by about 2.8x, and reduces the neutron power fraction to about 9.4% of total system power. Storage of the T produced in the other branch yields another ^{3}He after T decay. This, too, can be reinjected to give 15.7 MeV/DD reaction (DDcatB), over 4.0x higher than from DD alone. These -catA/B cycles are the most promising of all combinations for near-term practical fusion power. EXL systems show gross gain over 10:1 (recirculating power < 10%) at net electric power 700-1000 MWe with thermal conversion efficiencies of only 35% in machines 3.5-4.0 m in radius, for system operation with conventional materials (stainless steels) at well-proven steam conditions (e.g. 2000 psia, 600-650°F).

It is thus logical to consider fusion R&D along a DD path that starts at the same size and with the same or higher B field and electron drive voltage/current as required for a final reactor power unit. Initial experimentation can be done using H with trace D additives, and all electron power loss, ion upscattering, system ion/electron recirculation flow stability, control and fueling issues be determined without significant fusion reactions. First power production can use D, only, and small scale testing with stockpile ^{3}He can be done to verify stability, and operational control. The DDcatA cycle requires addition of an exhaust system T/^{3}He extraction and separation plant, and injection of the recovered ^{3}He into the EXL system. The final and experimental power devices here are the same relatively small size (ca. 4.0 m radius), at modest power (ca. 100-200 MWe). Because of this, the operational cost and time scale for this development process can be kept below $250 M and within 7-9 years, if a vigorous effort is undertaken.

By this means, the DDcatA power economy can be started without recourse to problematic extraction of ^{3}He from sea floor vents, or development of the entire space flight infrastructure needed to obtain ^{3}He from the Moon. The eventual saturated DDcatB cycle will also be self-sustaining, with no exogenous ^{3}He requirement, and only 5.5% neutron power fraction. The cost of power from such systems/cycles is inherently significantly smaller than from any other power source. The balance-of-plant for thermal DDcatA/B cycles is the same as that for coal, oil, or nuclear fission plants, but the fusion power core is very much smaller and less expensive. By use of the EXL concept and the R&D approach from D to self-generated-^{3}He-catalyzed DD systems, economically practical fusion power could be developed and deployed within 10 years.

Further Evaluation of the Helium Potential of Mare Tranquillitatis

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The study of the availability of Helium-3 from the Moon is currently focused on Mare Tranquillitatis, owing to its vast extent, its accessibility, and the presence of large areas of high-TiO_2 regolith that should be enriched in helium. The He-3 content of minable regolith has been estimated at 7,000 tonnes, but this only is a preliminary estimate based on sampling at the Apollo 11 site, reflectance mapping, and study of high-resolution photographs of the Apollo 11 and Ranger VIII sites. The true He potential of the Mare must be determined by systematic exploration. Reflectance data must be calibrated against samples representing the range of reflectance characteristics, and current spectral reflectance maps must be revised accordingly. Areas of high-TiO_2 regolith physically minable in terms of surface characteristics shown by high-resolution photographs should then be scanned by robotic vehicles equipped with ground-penetrating radar, to determine variations in depth of regolith and distribution of blocks too large to be handled by the mining system. Areas ultimately classified as minable should then be systematically sampled for variations in He content. Finally, mining and processing methods should be tested by pilot operations on the Moon.

Reflectance data currently available indicate that first exploration of Mare Tranquillitatis should be directed to the western part of the mare. An area centering on 9 N. 20 E. is recommended from work done to date.

Overview of the Mirror Fusion Propulsion System (MFPS): An Optimized Open Magnetic Field Configuration Using D-^{3}He

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The application of fusion power to space propulsion requires rethinking the engineering-design solution to controlled fusion energy. Whereas the unit cost of electricity (COE) drives the engineering-design solution for terrestrial utility-based fusion reactor configurations; initial mass to low earth orbit (IMLEO), specific power (kW_{thrust} / kg), and reusability drive the engineering-design solution for successful application of fusion power to space propulsion.

We briefly describe the principles of a proposed fusion reactor configuration - the thermal barrier tandem mirror (TBTM) - and summarize a recent design study called MINIMARS. MINIMARS represents a terrestrial utility-based engineering-design solution to the TBTM configuration that includes: (1) a deuterium-tritium fuel for ease of ignition, (2) a smooth reactor-core magnetic field using encircling magnetic-pancake coils to aid plasma stability, and (3) a necessarily large refrigeration system to maintain the normal-superconductor at 4.2 kelvin. The resulting specific power is less than 0.1 kW_e / kg at a total mass greater than 6,000 tonnes.

In contrast to the terrestrial design, MINIMARS, we describe in detail the application of three primary design principles to adapt and optimize a space-propulsion-based engineering-design solution to the TBTM configuration. These three design principles are: (1) optimize the plasma fuel, fuel mix, and temperature to minimize waste radiation, (2) provide maximum direct access to space for the remaining waste radiation, and (3) operate components as passive blackbody radiators when possible. The resulting engineering-design solution includes: (1) a deuterium-helium-3 fuel at a specific fuel-mix and temperature to minimize waste radiation, (2) a rippled central-cell magnetic field with a "transparent" electrically-conducting wall to maximize the direct access to space for waste radiation while simultaneously enhancing plasma stability, and (3) operating the electrically-conducting wall and outer-neutron and x-ray shields as passive radiators to minimize the total cooling-system mass. All of these engineering-design solutions taken together yield the Mirror Fusion Propulsion System (MFPS) with an optimized specific power of about 4 kW_{thrust} / kg propulsion plant at a propulsion-system IMLEO (active cooling system mass included) of about 500 tonnes.

We describe the physical characteristics of MFPS subsystems which include modularity and reusability. Modularity offers increased performance and reusability offsets the relatively high IMLEO. We characterize and compare the impact of helium-cooled normal-superconducting and hydrogen-cooled high-temperature superconducting magnet systems in MFPS.

We briefly describe the performance advantages of MFPS for two candidate missions: (1) a 90-90-90-day human-piloted Mars-exploration mission with continuous mission-abort capability and (2) an extra-solar-system mission, called the solar-gravity-lens-orbiting (SGLO) mission, using a reduced-performance post-design-life MFPS.

The potential performance of this fusion-based propulsion system, with the added benefit of providing technology that supports solutions to our future energy needs on Earth, argues for a sustained commitment to fusion research as applied to space propulsion in the 21st century.

The Lunar Environment and He-3 Mining

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ABSTRACT

The primary environmental factors that must be considered for human operations on the lunar surface are: (1) Low gravity: 1/6-th that of Earth; (2) Hard vacuum: less than 10^{-8} torr; (3) Fourteen Earth-days of sunlight and fourteen days of darkness; (4) Thermal extremes at the surface: typically -170°C to 110°C; (5) Thermal near-constancy below 1 m: about -20°C (due to the insulating properties of granular soil in vacuum); (6) Cosmic radiation and solar flares: humans cannot be exposed on the surface for long periods; and (7) Dust: the lunar soil is very fine and, because of electrostatic charge, adheres to spacesuits, metal fittings, optical lenses, etc. Housekeeping is a major headache.

However, there are definite advantages from a mining point of view: except for solar flares, the "weather" on the Moon is precisely predictable and there is no wind, rain, snow, or ice. Furthermore, there is no overburden to be stripped: the ore is the surficial lunar soil and is directly accessible.

The top few centimetres of lunar soil are loose and fluffy, but the density increases very rapidly with depth. Just to 5 to 10 cm below the surface, the soil density is much greater than can be accounted for by the weight of the overlying soil; denser, in fact, than could be achieved with heavy compaction equipment on Earth. This phenomenon is due to meteorite impacts, which stir and loosen the surface, and at the same time, shake and densify the underlying soil. As a result, the lunar soil is quite strong and is capable of supporting virtually any conceivable structure.

Trafficability on the lunar surface is well-understood: The energy consumed by the rolling resistance of the soil is small compared to other energy losses, most notably inertia. The cruising speed of a lunar roving vehicle is limited by surface roughness and terrain to about 6 to 7 km/hr. Slope-climbing of a wheeled-vehicle is limited to 23° without grousers; and to about 30° with grousers.

Excavation on the lunar surface, whether for mining or habitat installation, will require mechanical equipment. Vertical faces in the lunar soil can be excavated to a depth of 2 to 3 m. Once excavated, the lunar soil cannot be re-compacted to its original *in situ* density and, consequently, it will occupy about 15% more volume.

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ARIES-III Second-Stability, D-^{3}He Tokamak Reactor Design

(Abstract not available at the time of printing.)

Near-Term Experiments on D-He^3 Burning*

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An interesting goal that can by pursued on the near-term is the study of the conditions where the 14.7 MeV protons and the 3.6 α-particles produced by D-He^3 reactions can heat a well confined plasma. For this purpose an axisymmetric toroidal configuration has to be able to

i) sustain a sufficient current ($I_p \gtrsim$ 6MA) to confine the proton orbits at birth
ii) have a sufficiently high density that the slowing down time of both the protons and the α-particles is shorter that the electron energy replacement time of the thermal plasmas in which they are produced.

On this basis the design characteristics of the Ignitor-Ult experiment, where the plasma current can be raised up to 12 MA and D-T ignition conditions can be attained with peak densities $n_o \simeq 10^{15}$ cm^{-3}, are suitable to investigate of the fusion heating due to D-He^3 reactions. The Ion Cyclotron Heating system that has been adopted plays a central role in that the power that it can supply to the plasma can be focused on a small fraction of its total volume. This system can deliver up to 18 MW in a total plasma volume of about 10m^3 and can be used to bring a minority population of He^3 nuclei in a deuterium plasma up to energies of the order of 1 MeV. Under these conditions several megawatts of D-He^3 fusion power can be produced while the peak plasma density is in the range 2 - 4 $\times$ 10^{14} cm^{-3}. In these conditions, the onset of sawtooth oscillations, that could prevent the electron temperature to maintain relatively high values, can be suppressed and the slowing down time of the fusion products can be shorter than the expected energy confinement time. An issue that is of special importance is whether th 14.7 MeV protons will lead to the excitation of new types of collective modes relatively to those, due to high energy particles, that are known at present.

The criteria that have been followed for the design and construction of the key components of the Ignitor machine have been adopted to identify the parameters and carry out the feasibility studies of a high field experiment that was proposed at first in 1980 with the intent to reach D-He^3 fusion burn conditions[1] on the basis of existing technologies and knowledge of plasma phsyics. This is called Candor[1] and is capable of producing plasma currents higher than 20 MA in magnetic fields $B_T \gtrsim 13T$. Unlike Ignitor, Candor would operate with values of β_p around unity with the central part of the plasma column in the Second Stability Region. D-He^3 ignition in this case can be reached by an appropriate combination of ICR heating and α-particle heating due to D-T fusion reactions that have the roles of a trigger.

*Sponsored in part by the U.S. Department of Energy
This work is the result of a collaboration that has involved F. Carpignano, P. Detragiache, S. Migliuolo and M. Nassi.

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[1] B. Coppi, *Phys. Scripta* **T212**, 590 (1982)

My Perspective on D-3He Fusion

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ABSTRACT

The fusion reaction of deuterium with helium-3 has been recognized for more than 20 years as a possible basis for fusion energy. Relative to the reaction of deuterium with tritium, the advantages of non-radioactive fuel and fewer product neutrons are recognized. However, the advantages have been balanced by other factors: higher collision energy or temperature required, scarcity of helium-3, issues of conversion of the fast charged fusion products to heat or electricity. As a consequence it has been common to conclude that helium-3 fusion could be an advanced follow-on to tritium fusion.

That view could change because of better knowledge of helium-3 availability and keener understanding of how to employ the helium-3 fuel cycle. We now know of helium-3 from deep geologic sources and on the surface of the moon. This takes away the simple rule that "there is no helium-3", but questions surrounding costs of recovery will be important. The issue of physical means of harnessing the reaction of deuterium with helium-3 is more subtle. The leading confinement schemes, tokamaks and inertial, may not be able to effectively use helium-3. Then the "follow-on" notion is not quite valid and changes to emphasis on alternate confinement approaches specifically for helium-3.

NON-ENERGY APPLICATIONS FOR FUSION

John M. Dawson, UCLA

Abstract

Non-Energy Applications of Fusion Reactors are possible. The direct use of the 14.7 Mev protons from the D-^{3}He reaction for the production of positron emitting isotopes for medical, industrial, and scientific uses are of particular interest. Inside a working D-^{3}He reactor the 14.7 Mev proton flux is of the order of 10^{22} cm^2/sec, and in existing experimental tokamaks fluxes of 3 x 10^{18} cm^2/sec can exist. Large numbers of proton rich nuclei can be produced. The value of such isotopes, when used in medicine is very large (~\$$10^{12}$/gm). It is possible to have an economical reactor for a machine that does not break even in terms of energy. Existing research devices can produce interesting quantities of isotopes for experimental and demonstration purposes. A fusion reactor could reduce the cost of positron emitters significantly. This could open up a wide range of new industrial and scientific uses. The production of positron emitters, as well as some potential applications, will be discussed.

INDUSTRIAL PERSPECTIVES ON HELIUM-3 AND FUSION POWER

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The interest of industry in D-^{3}He fusion power will depend on their perception of the proponents as: (1) crazies, (2) radicals or fringe minorities, (3) innovators, (4) mainliners, or (5) visionaries. If fusion is perceived as at or near either end of this spectrum, industrial interest will be low. Innovation—where substantial benefits can be achieved on a relevant time scale—will be most attractive to industry.

If the goal of fusion were D-^{3}He, two possible approaches are:

1. Follow existing track to D-T and carry D-^{3}He as 'second generation.'
2. Optimize the development path so that D-^{3}He is the 'first generation.'

Depending on the choice, near-term programs would be radically different in such areas as materials development, concept improvement, and some technologies. The first approach is not attractive to D-^{3}He advocates because it attaches no urgency or priority to their work. The second approach is not attractive to most fusion scientists because it threatens most existing groups. There is a third approach:

- Maintain the near-term momentum of the D-T program.
- Go slow on long-range D-T technology, e.g., 14-MeV neutron testing.
- Initiate an intense near-term program on physics approaches to optimum D-^{3}He systems.
- Set up a decision point on whether to proceed toward D-T as 'first generation,' or switch to D-^{3}He.
- Involve industry on the front end of the search for a D-^{3}He development path.

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Concepts for Industry Involvement in Lunar Exploration

(Abstract not available at the time of printing.)

Overview of Apollo Studies and Economic Assessment of Several Proposed Variations

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Highlights of the Apollo series of D-^{3}He conceptual reactor studies are briefly summarized in this paper. The 1000 MWe designs operate in the first-stability regime and employ dual energy recovery systems: direct conversion for synchrotron radiation power and thermal comversion for neutron, bremsstrahlung, and transport power. A key feature of all Apollo designs is the low neutron production that reduces the damage to the structure and eliminates the need for first wall replacements during the entire reactor lifetime. Considerable reduction in the required shielding space results from the low neutron production and the absence of the tritium breeding blanket. Three coolants, namely water, organic coolant, and helium, were considered in the various designs with different thermal cycle efficiencies. The impact of material choice and shield design on the overall machine parameters and cost of electricity was assessed. The consequences of utilizing recent concepts for high-efficiency current drive will be explored. The safety and environmental features of the designs and the high system availability allowed the D-^{3}He tokamak reactors to compare favorably with tokamak D-T fusion reactors.

The Physics of Apollo: A D-^{3}He, First-Stability, Tokamak Reactor

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The critical physics considerations and issues for burning D-^{3}He fuel in the Apollo first-stability tokamak reactor will be assessed. These include plasma energy confinement, fusion-ash transport, current drive, startup, and synchrotron radiation energy conversion.

D-^{3}He tokamak reactors require both a high plasma current and a high magnetic field in order to provide good energy confinement and overcome the relatively low power density in a D-^{3}He plasma. In the first-stability regime, where beta values are very low ($\beta < 0.1$), the optimum magnetic field in a tokamak will be near the technological limits (~21 T at the magnet, using Nb_3Sn superconductor). The optimum value of the plasma current is a trade-off between confinement and the power required to drive the current. Because neutral-beam and radio-frequency current drive have been found to be inefficient, only driving ~0.05 A/W, there is a great deal of present interest in advanced current-drive techniques that promise much higher efficiencies. These include compact-toroid injection, helicity injection, and fusion-product amplification of lower-hybrid waves.

The Apollo design drives a portion of the plasma current by synchrotron radiation, using angled waveguides to absorb momentum in a preferred direction. The synchrotron radiation travels down the waveguides into separate chambers where rectifying antennas (rectennas) are used for high-efficiency energy conversion.

A balance must be sought between the need for good energy confinement and for sufficient fusion-ash transport to keep the ash from choking the plasma. This translates into the requirement that the ratio of fusion-ash particle confinement time to bulk-plasma energy confinement time be less than ~2. For startup, the key question is whether pure D-^{3}He startup will be possible or a D-T boost phase will be necessary.

Potential for D-^{3}He Experiments in ITER

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In order to determine the feasibility of achieving a D-^{3}He fusion reactor based on the tokamak concept, it is desirable to do meaningful experiments with D-^{3}He fuel in tokamaks being designed for D-T experiments. The objective of these experiments would be to test important plasma physics issues, such as heating, current drive, transport, stability, radiation losses, ash accumulation, etc., at the densities and temperatures expected in a D-^{3}He plasma. Investigation of these issues in a facility designed for the mainline D-T approach would allow an early resolution of these important physics issues before a major commitment of funds is made to a D-^{3}He research program.

The obvious choice for a D-T facility in which to do D-^{3}He experiments is ITER. An earlier investigation[1] of the potential for D-^{3}He experiments in CIT and ITER showed that, using currently fashionable physics assumptions, near breakeven could be achieved in ITER without major changes in the facility. Achieving breakeven required an increase in the magnetic field at the magnet as well as a change in the plasma shape, although within the existing vacuum chamber. The parameters of ITER were those of the CDA phase of the ITER project. Since that time ITER has grown from a major radius of 6 m to 7.75 m and the magnetic field at the plasma has increased from 4.85 T to 6 T. In this study we revisit the question of whether meaningful D-^{3}He experiments can be done in the new larger ITER. Power balance calculations indicate that breakeven can be obtained with reduction of the major radius by 50 cm with an increase of the aspect ratio to 3.15 and an increase of the elongation to 1.95. The plasma still fits within the existing vacuum chamber. High Q operation can also be obtained by a small admixture of tritium into the plasma. Plasma stability and transport issues can be investigated in these plasmas at conditions representative of D-^{3}He fusion.

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Concepts for the Utmost Clean and Beneficial D-^{3}He Reactor

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This report will describe the preparation of materials for a D-^{3}He reactor that could make the radiation hazard potential up to a million times lower than that of present fission reactors. A comparison will be made of reactors based on closed magnetic traps (tokamaks, stellarators, etc.) with reactors based on open traps (tandems, FRC) in the areas of divertor properties, radiation shielding, direct converters, radial plasma transport, recycling and first wall design and its erosion, average beta values, plasma power density and economics.

It will be discussed why, in spite of tokamaks leading in the fusion porgram, it is necessary simultaneously with ITER construction to develop the tandem and FRC research and development.

Results of investigations will be presented on the central cell plasma in tandem mirrors: plasma kinetics, power balance, ash accumulation and removal, Q-values, the dependence on selective ion pumping, the principle of selective ion transport across an axisymmettrical magnetic field based on stochastic diffusion, the beta value limited by the ballooning mode of the interchange fluite instability and its dependence on the radial pressure profile, and analysis of the trapped particle instability.

Some consideration on low radioactivity helium-3 production on the earth will be presented.

REMOTE SENSING OF LUNAR ^{3}He

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A direct, accurate measurement of the location of high concentrations of ^{3}He in the lunar regolith is needed for the initiation of cost-effective mining operations on the moon. Gamma-ray spectroscopy has been successfully used to map the abundances and distributions of certain elements present in planetary regoliths. Helium-3 is unique among these elements since the gamma-rays produced in the $^3He(n, \gamma)^4He$ reaction are 20.5 MeV or above. Thus, detection of this gamma-flux should be free of interference from the gamma-rays of any other neutron capture reaction. Since ^{3}He is present in the relatively small concentration of about 10 parts per billion by weight, the flux resulting from the $^3He(n, \gamma)^4He$ reaction using galactic cosmic-ray (GCR)-induced neutrons will be extremely small. We propose to map the 20.1 MeV gamma-ray from ^{3}He during very large solar proton flares (VLSPF) to take advantage of the increased flux of solar cosmic-ray (SCR)-induced neutrons. The neutron production spectrum in the lunar regolith has been calculated from GOES satellite observations of the October 1989 VLSPF using the BRYNTRN charged-particle transport code. This spectrum is used as input for the ONEDANT neutron/gamma-ray transport code. The production of SCR-induced neutrons during a VLSPF is thus calculated to be several orders of magnitude greater than the production expected for GCR-induced neutrons. The production of 20.1 MeV gamma-rays is also calculated to be several orders of magnitude greater during a VLSPF. This method of mapping the 20.1 MeV gamma ray from the $^3He(n, \gamma)^4He$ reaction would also provide increased sensitivity for mapping other elements in the lunar regolith, and may allow the detection of previously unmapped elements in the lunar regolith as well as trace elements in the Earth's upper atmosphere.

BY-PRODUCTS OF LUNAR HELIUM-3 MINING

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The Moon is our closest substantial source of ^{3}He, and we may wish to use that isotope in commercial fusion. Helium-3 and electrical power generated from conversion of solar energy to microwaves may be the only realistic lunar products for use *on Earth* in the coming decades. The Moon has the potential, however, to supply a variety of materials for use *in space* -- from low-Earth orbit, to the Moon itself, and beyond. Possible products of lunar soil include construction materials, oxygen, and gaseous by-products of ^{3}He mining.

On Earth, we have well developed sources of materials we can use in space, and we have sophisticated capabilities to create others. Early lunar technologies will be primitive in comparison. For materials to be used in near-Earth space, the Moon nevertheless offers potential advantages over both the Earth and other objects such as asteroids. The Moon's proximity, with attendant short communication and travel times and greater safety, is an advantage over other objects such as asteroids. The Moon's intermediate, 1/6g gravity is an advantage compared to the lower gravity of asteroids; it is large enough to make familiar gravity-assisted separations possible and to anchor mining equipment in place. The Moon's gravity is also an advantage relative to Earth. It is low enough to provide a payload-to-liftoff mass ratio of ~50% (using conventional H_2-O_2 propulsion), superior to Earth's ~1.25 % (with the present reusable shuttle system, but obviously subject to improvement). Present launch costs to low-Earth orbit are discouragingly high. They can surely be lowered, which would seem to make use of Earth materials more attractive than use of lunar materials. Lower launch costs from Earth, however, make the use of lunar materials more attractive. This is because one of the largest barriers to the potential development of the Moon's resources is the cost of hauling equipment for mining and manufacture to the Moon, and that cost would be lowered.

Lunar materials other than ^{3}He are likely to become economical in applications where large masses of relatively simple materials are needed in space. Initially, lunar materials are most likely to compete well for applications such as using "soil" for heat and radiation shielding, glass and ceramic products for construction, and oxygen and hydrogen for propellant. Lunar products are less likely to compete effectively in applications requiring tight manufacturing tolerances or low total quantities, because then the costs of setting up lunar operations to produce them would likely exceed possible savings in transportation.

Of particular interest here are the byproducts that would be generated by ^{3}He mining. These include H, C, N, S, and noble gases. Like ^{3}He, these elements are released from lunar soils on heating. At the least, they would be massive contaminants to ^{3}He mining and purification. These elements and isotopes (except S) were virtually excluded from the Moon when it formed, but are abundant, although dilute, in the lunar "soils." They were deposited there as ions from the solar wind, which embedded themselves into soil grains (like ^{3}He). Thus, contrary to opinions that have been expressed by some scientists, the Moon has the necessary chemical elements in sufficient abundance to support life and a propellant industry. For example, there is enough H and far more than enough O in the outer two meters of lunar soil to produce 15% as much water as is contained in Lake Erie. Part of the ^{40}Ar and ^{4}He come from radioactive decay of U, Th, and K. Sulfur is somewhat concentrated at the lunar surface as a result of the Moon's chemical differentiation into mantle and crust. If released from the soils during ^{3}He mining, these elements should be conserved and used or stored, rather than exhausted into space.

One of the most valuable by-products of ^{3}He mining would be the experience we would gain in mining, manufacturing, and other operations on a planet other than Earth, whether those activities are done robotically, by remote teleoperation, or by local teleoperation with human intervention as needed. Such experience is invaluable when viewed as research, and research is, after all, the appropriate activity for probing such unknown territory as potential uses of extraterrestrial materials.

SAFETY ANALYSIS OF THE ARIES-III

D-^{3}He TOKAMAK REACTOR DESIGN[a]

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Abstract

The ARIES-III reactor study was an extensive examination of the viability of a D-^{3}He-fueled commercial tokamak power reactor. Because neutrons are produced only through side reactions (D+D→^{3}He+n; and D+D→T+p followed by D+T→^{4}He+n), the reactor has the significant advantages of reduced activation of the first wall and shield, low afterheat and Class A or C low level waste disposal. Since no tritium is required for operation, no lithium-containing breeding blanket is necessary. A ferritic steel shield behind the first wall protects the magnets from gamma and neutron heating and from radiation damage.

The ARIES-III reactor uses an organic coolant to cool the first wall, shield and divertor. The organic coolant has a low vapor pressure at the operating temperature required for good thermal efficiency. Radiation damage requires processing the coolant to remove and crack radiolytic products that would otherwise foul cooling surfaces. The cracking process produces waste, which must be disposed of through incineration or burial. We estimated the offsite doses due to incineration at five candidate locations.

The plasma confinement requirements for a D-^{3}He reactor are much more challenging than those for a D-T reactor. Thus, the demands on the divertor are more severe, particularly during a disruption. We explored the potential for isotopically tailoring the 4 mm tungsten layer on the divertor in order to reduce the offsite doses should a tungsten aerosol be released from the reactor after an accident.

We also modeled a loss-of-cooling accident (LOCA) in which the organic coolant was burning in order to estimate the amount of radionuclides released from the first wall. Because the maximum temperature is low, < 600°C, release fractions are small. We analyzed the disposition of the 20 g/day of tritium that is produced by D-D reactions and removed by the vacuum pumps. For our reference design, the tritium will be burned in the plasma. These results re-emphasize the need for low activation materials and advanced divertor designs, even in reactors using advanced fuels.

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ABSTRACT FOR UW SYMPOSIUM ON ^{3}He and FUSION POWER

Next Step in FRC Development

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Field Reversed Configurations (FRC) are probably the most attractive option for burning advanced fuels due to their high beta and unrestricted end-flow from a natural divertor. Unfortunately research on FRCs was halted in the US in 1992, along with research on most alternate concepts. The Large s Experiment (LSX) at STI Optronics was mothballed after only one year of operation, but the LSX facility has since been transferred to the University of Washington where it is being reconstructed and modified to perform a Tokamak Refueling by Accelerated Plasmoids (TRAP) experiment. Due to recent recommendations by various review groups, research on alternate concepts may again be contemplated, and plans have been formulated to utilize the TRAP formation and translation sections to inject a hot, low density, moderate flux FRC into a proposed new confinement chamber.

Experimental results from the one year of LSX operation will be reviewed. In particular, no tilt instabilities were seen up to s values (ratio of minor radius to ion gyroradius) of 8, and symmetric, peaked density profile FRC equilibria could be formed up to s = 4. These good equilibria not only exhibited complete stability (other then the normal rotating n=2), but had good energy and particle confinement, extending the empirical results obtained in previous smaller experiments. In addition, high electron temperatures, which are needed for both flux sustainment and favorable reactor energy balance, were obtained for the first time in simple formation experiments. The implications of these results for D-^{3}He reactors will be discussed.

The LSX experiments also explored the practical limits of flux trapping in Field Reversed Theta Pinches, which are in the range of several tens of mWb. Some auxiliary flux build-up technique will be needed to reach reactor level Wb flux levels. Momota and his group have proposed neutral beam flux build-up, which is also under consideration for the proposed LSX/mod experiments. However, the most favorable candidate, especially for a University sized facility, appears to be RF current drive in the form of rotating magnetic fields (RMF). RMF has previously been used to produce low energy FRCs, is being investigated for current drive in tokamaks, but has never been applied to preexisting hot FRCs. Both the experimental considerations, and reactor extrapolations of RMF flux enhancement and current drive will be discussed.

Characterizing the Lunar ^{3}He Reservoir

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The suggestion that the regolith of the Moon may contain a substantial source of ^{3}He for supplying D-^{3}He reactors on the Earth for several centuries has caused renewed interest examining earlier data from Apollo-returned rock and soil samples to elucidate further the potential of this possible lunar reservoir[1,2,3,4]. The primary source of ^{3}He found in returned samples of the lunar regolith is implanted solar wind helium. An enrichment in the finest fraction of the returned lunar soils is attributed to the surface correlation of gas concentrations expected from the shallow depth of implantation, and "gardening" of the regolith by meteoritic impact. The measured solar wind ^{3}He concentration in these soils has been reported to range from 0.4 to ~ 15 wppb, the highest concentrations are found in soil samples from comminuted mare basalts[4]. If the distribution of the lunar helium is, as expected, widespread to depths averaging a few meters, even such low concentrations will become attractive for mining scenarios when D-^{3}He fusion becomes a commercial reality[1]. Furthermore, the suggestion has been made that structural gas traps created by impact may reside beneath the lunar surface[5]. If such traps can be discovered, a reduction in mining and extraction costs below estimates from the initial scenario[1] may be won.

Aside from the need to map the entire lunar surface for He and other volatiles and to conduct robotic surface prospecting, there remains a need for new laboratory work on lunar materials returned by Apollo to answer important questions regarding the resource potential. Broad areas of need include improving the characterization of the helium ore mineralogy and petrology through studies of mineral and rock separates and artificially implanted lunar simulant, identifying and detailing the potential co-products generated by different modes of extraction, and assessing the efficiency of different extraction, separation, and storage techniques. The Lunar Base Research Group of the ESRL has experimental programs to address specific issues in these broad areas. We will report the progress of these ESRL activities.

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SYNCHROTRON RADIATION FROM HIGH-TEMPERATURE PLASMAS [1]

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Synchrotron radiation is an important energy loss mechanism in fusion plasmas. This is especially true for either D-T or D-^{3}He plasmas under conditions relevant for future fusion devices. Many reactor studies (e.g. ARIES, Apollo, ...) favour regimes with high average temperatures, peaked density and temperature profiles and high magnetic field strength on axis. In some cases also a low reflection coefficient at the first wall has to be used because of the choice of ceramics as first wall material. The choice of all these parameters strongly affects the role of synchrotron radiation in the overall power balance of a fusion plasma and its role in increasing the energy transport from the center to the plasma edge.

In addition to that, one in principal has the possibility to utilize synchrotron radiation for passive current drive in a tokamak. For that purpose, fish-scale like structures would be necessary at the first wall to convert the initially symmetric radiation into one with a strong asymmetric distribution to be able to drive a net current. Together with the bootstrap current this mechanism could generate an important contribution to the overall current.

The accurate computation of cyclotron radiation losses from fusion plasmas and of the pertinent energy transport mechanism from the center to the edge is thus very important for reactor grade fusion plasmas.

The calculation of synchrotron radiation losses, of related transport phenomena and passive current generation includes a variety of problems: (1) Calculation of emission and absorption coefficients for a wide range of plasma parameters and frequencies; (2) calculation of current drive efficiencies; (3) solution of the radiation transport equation in non-homogeneous plasmas; (4) proper consideration of a given geometry and (5) correct inclusion of wall reflectivity and mode mixing at the first wall.

In this paper a report is given on synchrotron radiation losses from different non-homogeneous plasma configurations (e.g. cylinder, screw pinch, field-reversed configuration, tokamak) numerically computed by solving the radiation transfer equation. In addition to that, a comparison is given between different calculational models, pertinent assumptions and results therefrom. The possibility for passive current generation in tokamaks is also discussed in some detail.

[1] Work supported by: Austrian Academy of Sciences and Department of Science and Research of Austria under Grant Nr. GZ. 77.781/2-25/91; Government of Styria.

Safety Characteristics of D-^{3}He Fusion Reactors

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A D-^{3}He reactor has the potential to be an inherently safer fusion reactor because most of the energy released in the plasma would be in the form of protons rather than neutrons. Only 1-5% of the fusion power is carried by fusion neutrons which are produced from the deuterium-deuterium (D-D) and deuterium-tritium (D-T) secondary reactions. Even though most protons thermalize on the background plasma, a small fraction would follow orbits that strike the reactor structure, producing radioactive isotopes or more neutrons as a result of (p,n) reactions. A detailed activation and safety analysis, where activation due to both protons and neutrons is considered, has been performed for a selected reactor design (APOLLO-L2) to identify the possible safety and environmental advantages of using the D-^{3}He fuel cycle. APOLLO-L2 operates for 30 full power years and has a steel water cooled structure. Results of the activation analysis showed that proton-induced activity represents a small fraction of the total radioactivity generated in the steel structure. A decay heat comparison showed that there is two to three orders of magnitude difference in the level of decay heat generated by fusion neutrons and protons at any time after shutdown. A similar analysis of the activity induced by neutrons produced through the different (p,n) reactions in the reactor first wall showed that even though this neutron source is generated within the first wall itself, it only results in a level of activity which is slightly less than that induced by protons within the first wall. The radwaste classification of the reactor structure has been evaluated according to both NRC 10CFR61 and Fetter waste disposal concentration limits. At the end of the reactor lifetime, its structure would easily qualify for shallow land burial as low level waste. Finally, The thermal response of the reactor shield following a loss of coolant accident (LOCA) has been determined up to two weeks after an unscheduled shutdown of the reactor. The maximum temperature the first wall reaches is 500 °C. The low temperature of the structure during a LOCA results in the release of a very small fraction of the radioactive inventory at the onset of an accident. Hence, APOLLO-L2 design achieves the inherent safety criteria with respect to activation products. The D-^{3}He fuel cycle has definite environmental and safety advantages over other fusion fuel cycles.

U.S. Army Perspectives on Lunar Resource Recovery and Utilization

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The U.S. Army Corps of Engineers is involved with space access, development and utilization by virtue of its traditional roles in exploration, Federal property and infrastructure maintenance, and contracting agent for Federal construction. Within these roles the Corps has been the construction contracting agent for other branches of the government for facilities involving launch, maintenance, and monitoring of spacecraft. The Corps was involved with topographic map preparation supporting missions to the Moon and Mars. The Corps has also been active in working with NASA in developing planning documents for fielding of large space structures and Lunar base design and construction. At this time it appears that helium-3 as a fuel for fusion energy may become the primary commercial and national incentive for returning to the Moon and establishing permanent facilities. The promise of fusion involves national security, health care, and Earth environmental improvement concerns. Lunar mineral resources will be required for construction materials for both Lunar bases and large orbital structures, and the Corps is concerned as it maintains large laboratories and databases for construction engineering technology. Lastly, the Corps will be involved with preparation of Environmental Impact Statements supporting Lunar surface activities.

Abstract for Second Wisconsin Symposium on ^{3}He and Fusion Power

PHYSICS ISSUES FOR LARGE ORBIT FUSION SCHEMES

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At the First Wisconsin Symposium on ^{3}He and Fusion Power we described a fusion idea in which ions are confined by a spherical electrostatic potential well produced by an electron cloud which is confined by a cusp magnetic field. If the ions are injected into the potential well with very little azimuthal energy, they will converge to a dense focus at the center of the sphere. Since that meeting we have investigated a number of physics issues which can influence the behavior of the convergent ions. The studies we will present include a detailed analysis of the collisional effects which will eventually destroy ion convergence, and a study of the stability of counterstreaming ion beams. The stability study is nonlocal, carried out for a spherical plasma with density increasing inward as $1/r^2$ and the ion beams converging radially. The results of other related studies will be presented as time permits.

History and Overview of ^{3}He Research

by

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The first atoms of ^{3}He were discovered 54 years ago (1939) by L. Alvarez and R. Carnog during an experiment to determine whether or not tritium was radioactive. Ten years later (1949), scientists used the ^{3}He isotope to produce the first $^3He(D,p)^4He$ fusion reactions, thus introducing society to the possibility of a clean form of fusion energy. The advantages of a greatly reduced level of radioactivity and neutron production from this reaction, as well as the higher temperatures required for ignition, were immediately apparent. In any case, it took another 13 years (1962) before the first fusion reactor using the D^{3}He reaction was proposed and that power plant was designed to propel rockets into space.

One of the main impediments to continued research into the D^{3}He fuel cycle was the well known fact that the terrestrial resources of ^{3}He were very limited (<100 kg) and it took until 1969 (30 years after its discovery) before the first kg of ^{3}He was collected in one place. This ^{3}He came from the decay of tritium in thermonuclear weapons. Such a small resource base would only power a single 1 GWe power plant for 1 year. However, the very next year (1970), a major discovery of ^{3}He was made by lunar geologists examining the Apollo-11 material. It was found that lunar regolith contained small, but significant amounts of ^{3}He deposited by the solar wind over billions of years. Unfortunately, this important piece of research escaped the fusion community at that time.

The interest in D^{3}He reactors continued in the 1970's and 80's, but fusion researchers remained oblivious of the important work conducted by NASA scientists in the Apollo program. It was not until 16 years later (1986) that this work was "rediscovered" by scientists at the University of Wisconsin who were looking for a larger source of ^{3}He for commercial fusion power plants. Analysis by the Wisconsin group showed that there was at least a million tonnes of ^{3}He implanted in the lunar surface and that it could be recovered with only small extensions of present day technology. Since 1 tonne of ^{3}He can release 19 GWy's of thermal energy, the ^{3}He on the moon could provide clean, and safe energy on the Earth for a 1000 years or more at the present usage rate.

The fact that there is a large source of ^{3}He available has stimulated a flood of new research on clean fusion reactors. Since 1986, there have been over 136 publications on D^{3}He fusion reactors and even the radiation free $^3He(^3He,2p)^4He$ reaction is now being examined for use in non-Maxwellian magnetic confinement devices. Uses of the by-product volatile gases (H_2, H_2O, N_2, CO, CH_4, and CO_2) from ^{3}He mining may stimulate the recovery of ^{3}He even before ^{3}He is needed to power fusion reactors. The challenge now is to build a major experiment to demonstrate the beneficial features of this safe and clean form of energy.

Comments on D-^{3}He IEC Experiments and Reactor Concepts

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An IEC employs injection of keV energy ions into a spherical configuration to create a potential well that in turn traps ions. Fusing ions in this trap have a non-Maxwellian distribution which is well suited to burning advanced fuels such as D-^{3}He. Small scale IEC experiments at the University of Illinois using deuterium, i.e., D-D reactions have been quite successful.[1] With operation at 80 keV the D-^{3}He reaction rate should equal that currently observed for D-D. Consequently, D-^{3}He experiments in the present size device are quite feasible and the resulting 14-MeV proton provides an important diagnostics for potential well studies.[2] D-^{3}He experiments planned for a scaled-up device are also discussed in the context of present experience with D-D reactions.

A key motivation for IEC development is the reactor potential, e.g., a recent EPRI panel cited this approach as potentially leading to the most attractive reactor from a utility point of view of any magnetic confinement approach.[3] Here we consider issues related to the extension to a gridded IEC to a reactor. A preliminary conceptual design for a 25-MW D-^{3}He reactor will be presented with stress on technological issues related to cooling and protection of the grids in both the IEC and proton direct convertor.

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Attractive Characteristics of D-^{3}He Fueled FRC Reactor

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Attractive characteristics of D-^{3}He fueled FRC fusion reactor "ARTEMIS" design are presented, which design[1)] has been carried out as a part of the joint US - Japan collaboration program on fusion research. A complete and consistent scenario to develop and to sustain a burning plasma is proposed by utilizing favorable characteristics of a field-reversed configuration as an advanced fueled fusion reactor. Although a development of 1MeV neutral beam sources and verification of the direct energy converter system are important issues for developing the fusion plant, all bases of the engineering applied to this reactor design are conventional. The completed design demonstrates attractive characteristics of the reactor as a commercial fusion plant. A high β FRC plasma allows us to constitute an economical electric power plant and estimated COE is as cheep as 32mills/kWh by introducing highly efficient direct energy conversion system into the plant. The life of the metallic materials can be more than full life of the reactor (30 years) and the safety of the reactor is inherent to D-^{3}He fueled fusion. The total amount of the disposed materials is small and intruder dose of these materials are so small that a surface disposal can be environmentally acceptable.

Discrepancies between required plasma parameters and present plasma parameters obtained from the laboratories are, however, quite large. It may be argent for us to start researches with reasonable devices for studying equilibrium, stability, and transport of an FRC and consequently to establish a reliable method to obtain and to sustain a fusion plasma.

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Utility Perspective on Clean Nuclear Energy

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Requirements for over 200 gigawatts new electric generating capacity in the United States during the first decade of the 21st Century will provide the opportunity for clean nuclear power to compete as one of the technologies to be selected by developers of generating capacity. Clean nuclear power must meet two primary acid tests: (1) economic on both a near-term and longer term basis; and (2) environmentally acceptable from a safety and nuclear waste disposal perspective.

The deregulated electric generation business of the future will select technology winners based on objective, competitive performance. The new owners of generating companies will be independent power producers/electric wholesale generators, competing utilities, and perhaps foreign companies. Generation will be sized to meet system growth requirements, probably in the 300-800 megawatt capacity range.

Innovative cooperation will be required to develop clean nuclear technologies which can meet the tests of economic and environmental acceptability with sufficiently clear advantage to overcome the current capital market aversion to the perceived risk of nuclear power. The current national and international concerns for clean air and management of gases which contribute to global warming may enable clean nuclear power to fill a role as a "green" technology. The long-term development of clean nuclear power will be required to meet national energy research demonstration and development goals through co-funded projects which offer near-term spinoffs of value to the government and industry.

PROSPECTS FOR NOVEL THERMONUCLEAR AND NON-THERMONUCLEAR FUSION*

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There is growing conviction in the world fusion program that although the scientific goals may be realized at some future date, our present, conventional, approaches to DT thermonuclear fusion, both magnetic and inertial, will not lead to attractive reactor products able to compete in the energy market place of the 21st century. This is a result of the projected low power density, high complexity, large unit sizes, and very high development costs. It is our contention that any breakthrough leading to economically-viable fusion will lie in new, unexplored physics areas rather than in refined engineering concepts for the present approaches. Consequently, we have commenced studies of several novel advanced fusion concepts, with the object of identifying schemes with the potential for a step-change in our approach to fusion energy. These schemes fall into two distinct groups:

(a) Novel thermonuclear approaches: We suggest that if we are constrained by thermonuclear operation, then the most viable approach may lie in pulsed, medium to high density systems which side-step the complexity and expense of the plasma/vacuum/solid-wall/magnet interface of conventional, low-density, magnetically-confined fusion. We are investigating both magnetically-insulated schemes, and novel ignitor, high density schemes. However, we are also considering low-density fusion in a novel, coil-free configuration that may have potential for $D\text{-}^3He$ operation.

(b) Non-thermonuclear approaches: We can directly trace the cost and complexity of conventional, thermonuclear fusion reactors to the constraints of a minimum required product of $n*\tau*T$ (magnetic confinement) or, equivalently, $\rho*R*T$ (inertial confinement). These requirements arise directly from the given value of the Maxwell-averaged reaction rate, $\langle\sigma v\rangle$. Therefore, we suggest that if we are to achieve a fundamental breakthrough in the physics of fusion, then the inherent limitations set by either the thermal averaging and/or by the cross-section itself must be circumvented. This is particularly true if we are ever to realize clear economic viability with the advanced fusion fuels such as $D\text{-}^3He$. Accordingly, we are studying some new, non-thermonuclear possibilities including non-thermal schemes, schemes which circumvent the Coulomb barrier, and shape-(not spin) polarized, advanced-fuel fusion. The latter may have potential for the higher-Z, deformed-nuclei fusion fuels such as $p\text{-}^{11}B$ and $p\text{-}^7Li$.

For any such advanced physics schemes to be considered serious contenders, they must be coupled with engineering realizations in order to clearly identify the potential for a step-change in capital costs, complexity and development path relative to our present concepts.

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D-^{3}He, Second Stability Tokamak Reactor Design

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An update of the parameters of the design and report on analyses of the main critical issues of the modest magnetic field D-^{3}He reactor design are presented in this paper. This includes plasma confinement, beta limit and the second stability regime, divertor problems, thermal-to-electric energy conversion and structural features of the design.

The approach to the solution of the first two problems is based on the experimental data obtained from tokamaks with a poloidal divertor. The energy confinement time in the experiments can exceed by 3.6 times the value obtained from the ITER scaling law for the L-mode. This value is used in the design.

The maximal central beta of about 44% was attained in DIII-D at a rather peaked radial plasma pressure profile. In the reactor design, the plasma density, temperature profiles and, hence, the pressure profile close to those obtained in the experiments on DIII-D are considered. The theoretical consideration of high beta production at the transition to the second stability zone cannot completely explain the experimental results on DIII-D. The experimental results at our disposal are assumed to be initial data for the reactor design. Particular attention is paid to the effect of density and temperature profiles on the reactor parameters.

The problem of a divertor allowing one to remove the heat from the plasma and to pump the reaction products out is the most complicated tokamak-reactor problem. An opportunity to use a gaseous and radiating divertor is discussed. The solution to the divertor problem in the D-^{3}He reactor can be similar to its solution for ITER in many aspects. Other possible solutions to the problem are also considered in the paper.

A new aspect of the D-^{3}He reactor in comparison with the DT reactor is the conversion of thermal energy into electricity. On the basis of the experiments on JET and DIII-D the principal problems of fusion energy utilization, using direct thermal-into-electric energy conversion are considered. This gives an opportunity to increase the reactor efficiency and to make it greater than the efficiency of a thermal cycle, characteristic of the best functioning electric power plants with the steam turbine cycle.

Optimization of the reactor plasma parameters at various plasma pressure profiles has allowed us to determine the set:

$$R = 8\text{m};\ \ A = 2.5;\ \ K = 2{:}\ B_0 = 6\text{T};\ \ \langle\beta\rangle \cong 18\% : \langle T\rangle \cong 40\ \text{keV}\ .$$

The control over the plasma pressure and current radial profiles can be one of the main tools for the transition from the low efficiency mode of operation to that with high efficiency.

Self Colliders for D-^{3}He Fusion

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High beta self-consistent equilibria are obtained. For these equilibria, almost all of the particle orbits are betatron orbits rather than the adiabatic orbits of conventional magnetic confinement systems usually considered for fusion. Conditions required for long-wavelength/low frequency stability are considered. If they are satisfied, classical confinement would be expected.[1] Classical estimates of slowing down and diffusion are made for D, He^3 and the fusion products T, He^4 and H. These estimates are based on Coulomb collisions and test-particle models rather than solving the Fokker-Planck equations. It is, however, essential to include some collective effects such as the inductive electric fields that arise from current decay. Considerations of self-sustained fusion reactions are based on these classical estimates.

[1]N. Rostoker, F. Wessel, H. Rahman, B.C. Maglich, B. Spivey, and A. Fisher, Phys. Rev. Lett. 70, 1818 (1993).

D-^{3}He MIRROR REACTORS

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The prospects of mirror devices in the context of the D-^{3}He reactor development are based on the demonstrated ability of mirrors to operate at the beta values approaching 100% and on the natural accessibility of their end sections for installing direct energy convertors. An intrinsic stability of mirrors is also their important advantage.

The paper summarizes those of the recent achievements in mirror experiments and theory that are most important from the viewpoint of D-^{3}He reactor applications: development of MHD-stable axisymmetric configurations, creation of microstable sloshing ion populations and detailed studies of the thermal barrier concept.

After a general overview of D-^{3}He mirror reactor schemes proposed so far, the feasibility of a particular version of such a reactor with a very low neutron production is discussed. This version is based on the two-component approach, when a relatively cold deuterium plasma serves as a target for the fast ^{3}He ions. The necessary requirements to D-^{3}He injectors and direct energy convertors are derived. Conclusion is drawn that, though very high, these requirements don't seem incompatible with any of the basic physics and technology limitations.

Magnetic Fusion Propulsion: Technology for Opening the Solar-System Frontier

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The exploration and development of the Solar System requires propulsion capabilities that only D-^{3}He magnetic fusion power appears able to deliver. Both conceptual design studies and generic arguments indicate that space propulsion systems based on D-^{3}He magnetic fusion reactors can provide performance dramatically beyond that of chemical, fission, and D-T fusion rockets for long-range missions. D-^{3}He fusion's capabilities include flexibility, a specific power of 1–10 $kW_{thrust}/kg_{reactor}$, and exhaust velocities up to ~0.18 c (c ≡ speed of light). Such capabilities, for example, allow two-month missions to Mars with the same payload as nine-month chemical missions or allow greatly increased payloads for longer durations. More distant missions, such as to the gas giant planetary systems, show D-^{3}He fusion to even better advantage.

The mass estimates for D-^{3}He fusion propulsion systems can be made with some confidence, because the masses of the key components—shields, magnets, radiators, and refrigerators—can be calculated with good accuracy. The main uncertainty lies in the systems for input power and power conversion, but these corrections should only be tens of percent.

D-^{3}He magnetic fusion will open the Solar System to humankind. Besides propulsion, fusion energy can provide power and materials processing capabilities. Three typical applications will be transporting humans and supplies to settlements, accessing the vast resources on asteroids and moons, and enabling scientific outposts analogous to antarctic bases.

Assessement of First Wall Lifetime in D^3He and DT Reactors with Impact on Reactor Availability

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In a tokamak fusion power reactor utilizing the D-^3He fuel cycle, only a small fraction of the fusion power (~5%) is carried by neutrons. About 60% of these neutrons are 2.45 MeV neutrons produced from DD reactions and the rest are 14.1 MeV DT neutrons. This compares to the case of DT fusion reactors where 80% of the fusion power is carried by 14.1 MeV neutrons. Hence, the neutron wall loading at the first wall of a D^3He reactor is much lower than that in a DT reactor of equivalent power. As a result, the rate of neutron damage and gas production in the first wall of D^3He reactors is lower than that in a DT reactor by more than an order of magnitude. The first wall lifetime is determined primarily by neutron damage and gas production rates. Frequent replacement of the first wall and blanket is required during the lifetime of a DT power reactor. Up to 10 replacements may be needed depending on the structural material used and the peak neutron wall loading. On the other hand, the low neutron wall loading in a D^3He reactor implies that first wall and shield change out is not required during the whole reactor life. In this paper, the first wall lifetime will be compared for D^3He and DT reactors using different structural materials. The down time required for replacement of first wall and blanket in a DT reactor will impact the reactor availability and consequently the cost of electricity. An attempt to quantify the impact on availability will be made for DT reactors using different structural materials.

Deutsches Aerospace-ERNO Perspective on He-3 and Power from Space

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ABSTRACT

Extraterrestrial power generation and delivery to Earth has been a long term application of space technology that ERNO Raumfahrttechnik GmbH has investigated since 1985 through the Global Solar Energy Concept (GSEK) project. As the name indicates, consideration of Helium 3 dependent fusion power was excluded. The availability of information about the potential for ^{3}He + D fusion has improved with the publishing of a few papers per year. However, the raising of awareness of this option has to overcome an established corporate vision of the space business future. The Helium 3 option has required advocacy from within the company and stimulus from customers such as the European Space Agency. It has now attained inclusion in corporate "working group" discussion papers but in the frame of long term projects such as planetary terraforming. Informed scepticism is the next barrier which the Helium 3 advocates must overcome. The conventional awareness of fusion power is that 50 years of research will be necessary before commercial activity. The prospect of Helium 3 fusion power is dismissed by people who merely quote the scientific journals. Within DASA-ERNO an initiative has begun to collect information about the prospects for Helium 3 fusion power. Internal research funds will be allocated to support data gathering and acquisition of study contracts which aim to examine the potential of Helium 3. The answers from these investigations will either increase corporate interest to a level similar to that which sustains the current GSEK effort or continue at a very low level of enthusiast interest. This paper elaborates the arguments and types of answers that may be needed to pursuade corporate chief executives that the profit may be achievable with moderate investment risk from a share of the lunar Helium 3 mining industry and support infrastructure business .

Coaxing He3 From Lunar Regolith; Processes and Challenges

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The discovery of vast quantities of He-3 on the moon in 1985 has reignited the prospects for near aneutronic fusion and all the benefits which accrue from it. Although the total amount of He-3 on the moon is enormous, it exists in the regolith in the ppb range. Experiments on lunar regolith samples brought to earth by the Apollo astronauts and Russian LUNA robots have shown that solar wind products can be extracted by heating them to 700°C, which releases ~85% of the He, along with large quantities of H_2, CO, CO_2, CH_4 and H_2O. He-3 extraction rate depends on the amount of energy available for heating. It is assumed that a 100 m diameter solar dish mounted on the lunar surface can beam energy to a 10 m diameter dish mounted on a lunar miner. Some 80% of this energy must be recycled within the miner to achieve a reasonable production rate. This paper discusses the operation of a mining machine which excavates, beneficiates, heats, cools and redeposits the regolith back on the lunar surface, while collecting and storing the extracted solar wind products. Processes needed for separating the various solar wind products are also discussed.

ENGINEERING DESIGN OF ARIES-III*

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Abstract

ARIES-III is a conceptual design for a D-^{3}He tokamak fusion power reactor. The ARIES series of reactor design studies was to investigate the different combinations of physics and engineering to evaluate the attractiveness of the tokamak as a power reactor. The ARIES-III is a 1000 MWe reactor that operates in the second stability regime. The plasma major radius is 7.5 m and the aspect ratio is 3. The plasma current is 30 MA and the toroidal field on axis is 7.5 T. The average neutron wall loading is only 0.08 MW/m^2. Since no tritium breeding is required in a D-^{3}He reactor, only a simple relatively thin shield is needed for magnet radiation protection. On the other hand, the peak surface heat flux in the FW is 1.86 MW/m^2. This has placed a premium on the design of the FW which should be capable of removing the high surface heat without exceeding temperature and stress limits.

Organic coolants have been used in fission reactors and useful experience of operating an organic cooled system was generated. Organic coolants can be used at a higher temperature than water (450°C vs. 350°C) with a much lower pressure (1 MPa vs. 20 MPa). The key reason that organic coolant was not considered for DT fusion reactors was the excessive radiolytic decomposition. However, in a D-^{3}He reactor, the neutron power is only about 4% of the fusion power. Therefore, the concern regarding radiolysis is much alleviated. The high surface heat flux in ARIES-III requires a coolant with good heat removal capability. In addition, the high capital cost and recirculation power require good thermal conversion efficiency. Furthermore, the first wall synchrotron reflectivity is required to be >0.99. Be coating was identified as the only choice of material with sufficient electrical conductivity to provide such reflectivity. To limit the evaporation of Be, a maximum Be temperature of 750°C was selected. This puts severe limitations on the FW and coolant temperature. These requirements resulted in the selection of the organic coolant for the ARIES-III FW and shield. Since the organic coolant is limited to about 450°C, advanced structural materials are not required. The low activation ferritic steel (modified HT-9) was, therefore, selected as the structural material. The overall features of the ARIES-III FW and shield design are described in this paper.

The low neutron wall loading removes many issues associated with a D-T fusion reactor. The first wall and blanket lifetime can be over 30 years, and replacement will not be required. The low activation and afterheat significantly increase the safety characteristics of the reactor. Non tritium breeding requirement simplifies the blanket and shield design. The D-^{3}He reactor has some most attractive safety characteristics of all nuclear reactors, including both fission and fusion.

However, the D-^{3}He reactor also put severe limitations on the physics and engineering designs. The engineering issues include first wall design, coolant selection, disruption considerations, plasma fueling, and waste tritium management. These issues will also be discussed.

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EVIDENCE FOR ABUNDANCES OF HELIUM-3 ON THE MOON: MODEL ASSUMPTIONS AND ABUNDANCES

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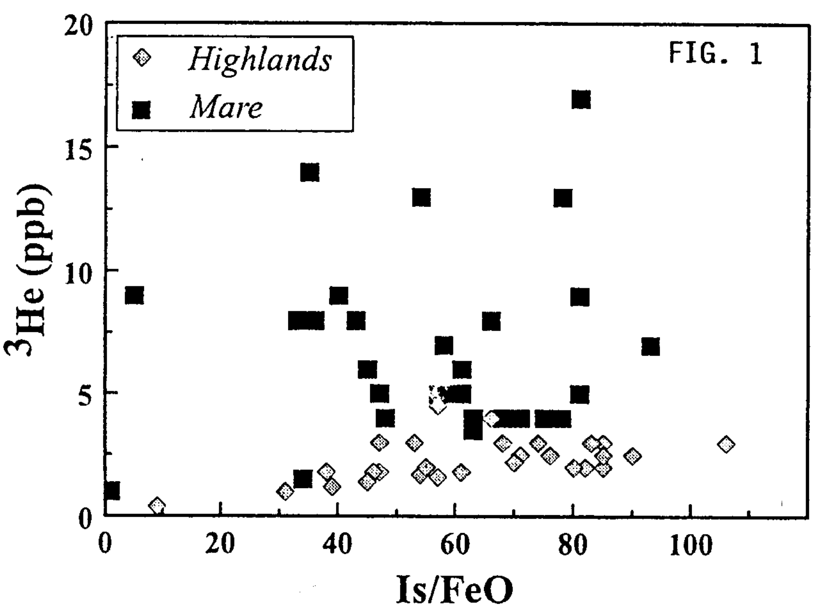
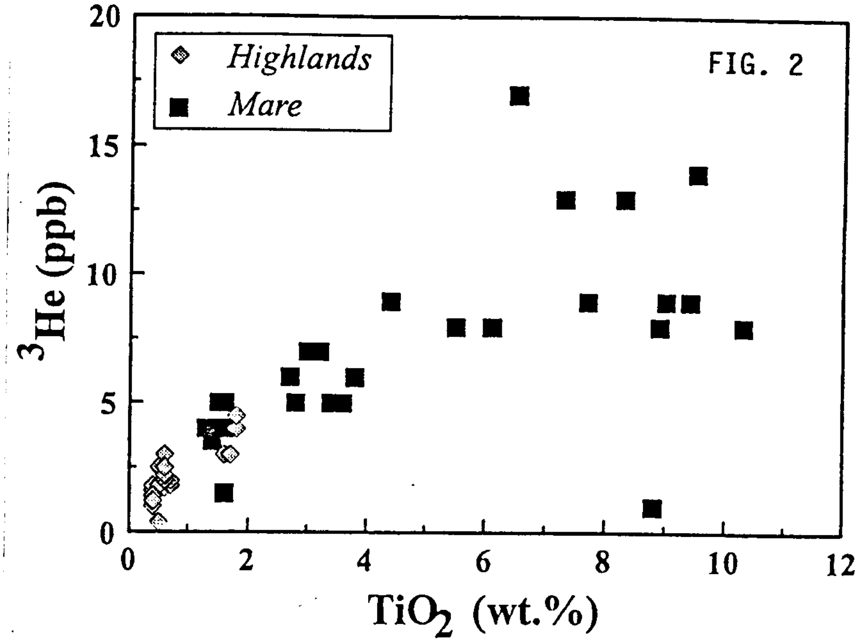
Since the first return of lunar samples, it has been known that the lack of a shielding atmosphere on the Moon permits solar-wind particles to impinge upon the lunar regolith and become implanted into the outer few 100 Å's of the various soil fragments. The abundances of hydrogen, helium, and carbon are particularly abundant (50-100; 3-50; 10-30 ppm, resp.; Taylor, **[1]**). It was Wittenberg et al. **[2]** that first pointed out to the fusion community that the lunar soil contains relatively large quantities of ^{3}He, compared to Earth. It has been the Fusion Technology Institute at the University of Wisconsin and under the direction of Dr. Gerry Kulcinski that has championed the cause for fusion of this ^{3}He **[3]**. In fact, ^{3}He may be the only true economic "ore" on the Moon.

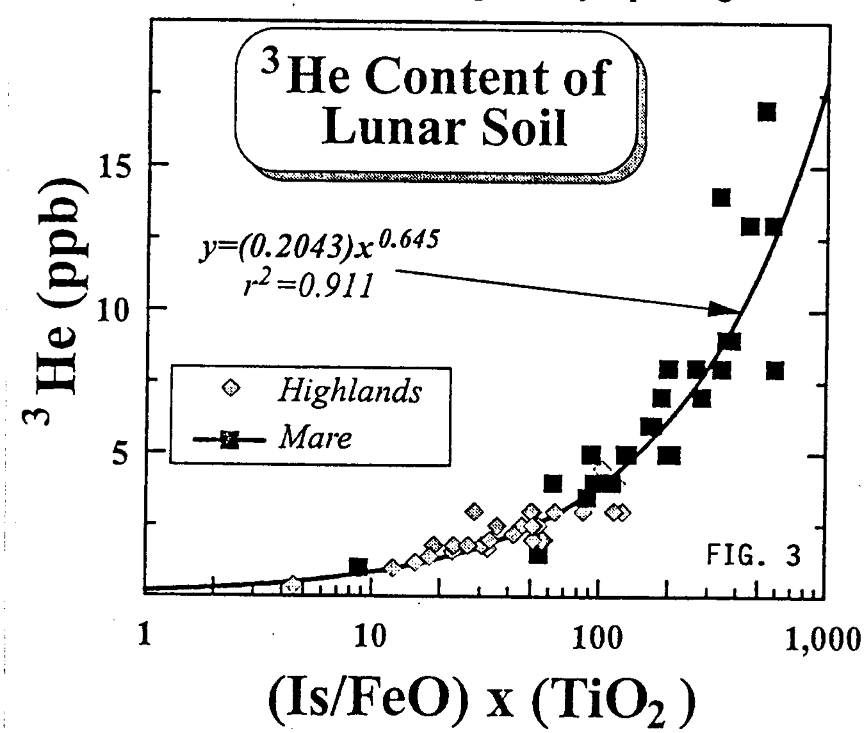
High-Ti mare basalt regions, such as at the Apollo 17 locale, appear to be the best areas for He mining (3-15 ppb ^{3}He), versus only 1-4 ppb in the Highlands **[1,4]**. The solar-wind contents of lunar soils are a function of ***exposure duration*** at the surface, ***mineralogy***, and ***grain size***. Exposure age is correlable with the amount of agglutinates in the soil. These fragile, aggregates of rocks, minerals, and glass fragments welded together by impact-produced glass are the key to the maturation process of the soil. When the soil is melted by small impacts, the soil already contains large amounts of hydrogen and carbon. These elements impose an extreme reducing environment, several orders of magnitude below the iron-wustite stability curve, which forces much of the Fe^{2+} in the silicate melt to Fe^o, causing saturation and precipation of billions of tiny Fe^o spheres. The Ferromagnetic Resonance signal for this "single-domain" (40-200 Å) elemental Fe, I_s, is divided with the total FeO content of the soil to give I_s/FeO, a parameter which increases as soil maturity (=exposure) increases **[5]**. There is a rough correlation between I_s/FeO and ^{3}He **[1]**, as shown in Figure 1, particularly for highland soils.



Ilmenite ($FeTiO_3$), and other oxide phases such as spinel, have trapping efficiencies (= retention) for solar-wind particles up to 10X that of the silicate minerals, such as olivine, pyroxene, and plagioclase. Therefore, there is a rough correlation between the TiO_2 content of a soil (as this reflects ilmenite content) and ^3He, as shown in Figure 2. In fact, the lack of correlation seen between I_s/FeO and ^3He for high-Ti basaltic soils, such as with Apollo 17 samples, is explained as a function of ilmenite content of a soil. Even though a high-Ti mare soil may be relatively immature, its ilmenite can contain considerable He. The He content of a soil is a strong function of both I_s/FeO and TiO2. Fig. 3 combines these two factors and demonstrates an excellent correlation with ^3He, a suggestion originally made by Jordan [6].



Because solar-wind particles are only present on the surface of grains, it is to be expected that solar-wind contents of lunar soils are a function of grain size. Typically about 50% of a soil is <50 um in size; however, this fine fraction contains 70-80% of the He_T. But the speciation of ^4He to ^3He, which varies 1200 to 3800 on the Moon, is strongly in favor of ^4He in the fine fractions, whereas the coarser sizes (i.e., >50 µm) contain less He_T, yet higher ^3He speciation [1]. Therefore, there may be little to be gained by separating the finer fraction of the soil for its ^3He. This would entail a process which will entail additional handling, versus using the bulk soil for its ^3He. Furthermore, the solar-wind gases are easily released from their sites on the outer surfaces of the soil particles by simple heating [7]. By 600-700 °C, over 80% of the H_2 and He_T have been evolved off the grains. In fact, a mining machine, patterned upon a continuous-feed, bucket dredge used on Earth for Au mining, has been designed for mining of lunar soil for volatiles [8].



Based upon profiles into the lunar regolith as revealed by the numerous cores taken during the Apollo and Luna missions, it is a fact that the solar-wind contents do not vary greatly with depth, at least down 2.8 m [1]. Therefore, it is a safe assumption that ***the He_T and ^3He contents of the upper several meters of the regolith are constant.*** What these contents are at greater depths is unknown and various other scenarios have been evaluated [9].

It should also be pointed out that ***the estimates for ^3He given below are conservative*** in that lunar soils may contain substantially more solar-wind volatiles than have been sampled by the Apollo missions. This is due to longitudinal variations in exposure to solar-wind particle flux. The Moon is shielded from solar wind by the Earth's magnetotail for 6-8 days/month [10]. At this time, the soils on the far-side and on near-side limbs would continue to receive the full flux, while the central regions of the lunar near-side would be effectively shielded. Over time, the center of the near-side should have received only 25-50% as much solar wind as the far-side and the limbs. The effects of solar-wind flux versus latitude may also be significant [11] such that regions near the poles of the Moon receive considerably less flux. Obviously, further lunar exploration will be necessary to determine the possibile ramifications of these flux conditions upon the solar-wind contents of lunar soils.

FACTOIDS ABOUT LUNAR REGOLITH

Physical Properties

- Regolith Depths are 2-5 m in maria and 10-20 m in the highlands;
- Average Density of the upper regolith $\simeq$ 1.8 gm/cm^3;
- One m^3 of regolith ~ 1.8 tonnes;
- Surface Area of the Moon ~ 3.8 x 10^{13} m^2;
- The Maria make up only 16%, the Highlands about 84%, of the Moon's surface;

Chemical Properties

- Most He measurements were taken on the < 1mm fraction of the regolith;
- The > 1mm fraction of the upper regolith is only 5-15%;
- He_T contents are constant with depth in the regolith;
- Maria have ^{3}He contents which average $\simeq$ 6 ppb;
- Highlands have ^{3}He contents which average $\simeq$ 3 ppb;
- Moon-Wide ^{3}He content of regolith ~ 3.5 ppb.

^{3}He ABUNDANCES IN THE LUNAR REGOLITH

- **Mare Regolith = 10.8 mg ^{3}He/m3; Highlands Regolith = 5.4 mg ^{3}He/m3**
- **The Area of a Mare Football Field to a Depth of 3 meters $\simeq$ 150 g ^{3}He;**
- **The Area of a Highlands Football Field to a Depth of 3 meters $\simeq$ 75 g ^{3}He;**
- ***Entire Surface of the Moon to a Depth of 3 meters ~ 720,000 tonnes of ^{3}He.***

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Second Wisconsin Symposium on ^{3}He and Fusion Power

Cost of ^{3}He from the Moon

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Abstract

The purpose of this report is to estimate the cost of ^{3}He from the Moon. Any estimate of this cost must be based on assumptions regarding the scale of ^{3}He use on earth and therefore the scale of the lunar mining operations, whether or not manned lunar scientific bases are present on the Moon, and whether or not volatiles extracted from the lunar regolith can be "sold" to the lunar colony. The calculations will be made assuming a "Lunar Mining Company" exists which holds a monopoly on mining ^{3}He on the Moon and which sells ^{3}He to terrestrial electric utilities and volatiles to the lunar scientific bases. The cost effectiveness of ^{3}He fusion plants in competing with coal and fission plants will determine the extent to which the lunar company can earn its cost of capital and the price of ^{3}He to terrestrial utilities.

DIRECT ENERGY CONVERSION SYSTEM FOR D-^{3}He FUSION

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A novel and highly efficient direct energy conversion system is proposed for utilizing D-^{3}He fueled fusion reactor, which provides an economical, safe, and environmentally sound energy plant.

In D-^{3}He FRC fusion reactor such as "ARTEMIS", more than 70% of fusion energy is carried by charged particles which escape directly out of burning plasma. By introducing these particles to direct energy converters (DEC) along the lines of force, it is expected to obtain fusion reactor with high plant efficiency. These particles consist of thermal components with energy of few hundreds keV and fusion protons with high energy of 15 MeV. In order to convert ion energy characterized by the above energy spectrum, we applied a pair of direct energy conversion systems each of which consists of a cusp-type DEC and a traveling wave DEC (TWDEC). In a cusp-type DEC, electrons are separated from the escaping ions at the first cusp and the energy of thermal ion components is converted to electricity at the second cusp DEC. Note that a cusp-type DEC avoids unnecessary bombardment losses of energetic protons which is inevitable to a traditional Venetian-Blind DEC. Since the orbit of 15 MeV protons is hardly affected by the cusp-magnetic field because of their high energy, high energy protons go through the cusp-type DEC and arrive at the TWDEC, which principle is similar to "LINAC". The applied electric voltage in the TWDEC is less than 1 MeV, which allows us to avoid flashover of the insulators.

The conversion efficiency of the cusp DEC is estimated as more than 60%. Protons with 15 MeV are guided to TWDEC and converted their energy to electricity with an efficiency of more than 70%. These DECs bring about the high efficient fusion plant. In this paper, optimum design parameter of DECs is given for obtaining high efficiencies of a reasonable scale fusion plant.

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NASA Perspective on Lunar Helium-3 Mining

(Abstract not available at the time of printing.)

Potential ^{3}He Resources for D-^{3}He Fusion Development

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Developing D-^{3}He fusion as an alternative to D-T fusion requires a supply of ^{3}He far exceeding presently available quantities. Test and demonstration reactors, necessary to demonstrate the commercial potential of D-^{3}He fusion, are estimated by Wittenberg et. al. to require a total of 152 Kg of ^{3}He by approximately 2015, when initial recovery of ^{3}He from lunar sources might begin. Sufficient ^{3}He is potentially available from a variety of terrestrial sources to meet the projected demand for ^{3}He if all of these sources begin recovery by 1995-2000. These sources include ^{3}He generated by the decay of tritium in the U.S. nuclear weapon stockpile or recovered from CANDU reactors, and ^{3}He extracted from natural gas wells. This paper will examine the potential ^{3}He recovery fraction from these sources, competing demands for ^{3}He, and the resources necessary to recover the ^{3}He; and suggest strategic decisions which must be made to ensure that sufficient ^{3}He is indeed recovered to carry out a successful development program. It will also examine the expected ^{3}He storage and transportation requirements to assess whether any new technologies will be required by the D-^{3}He program.

Non-Lunar ^{3}He Resources

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The earth's reservoirs and proposed nuclear reactions to produce significant quantities of ^{3}He are considered.

The formation of the earth-moon planetary system occurred by the accretion of large asteroids nearly 4.5 billion years ago. Some of these asteroids contained volatile gases with up to 20 ppb of He, having a ^{3}He/^{4}He ratio of 2×10^{-4}; however, due to heating during the accretion phase most of the volatile gases were ejected. Because no known nuclear reaction is capable of generating significant quantities of ^{3}He on earth and solar wind particles, carrying ^{3}He, are unable to penetrate the earth's atmosphere or magnetosphere, most of the present inventory of ^{3}He has existed since the creation of the earth. Conversely, alpha particles (^{4}He) have been continuously emitted by U and Th ores, diluting the virgin ^{3}He. As a result, present-day ^{3}He/^{4}He ratios range from 10^{-7} in natural gas wells up to 4×10^{-5} in ocean-island volcanic gases. Such volcanic gases suggest that the earth's deep interior may contain a million tonnes of ^{3}He; however, no viable extraction technique exists. The earth's atmosphere contains 4000 tonnes of ^{3}He but its concentration is only 7.7×10^{-12} volume fraction; hence, the recovery of ^{3}He requires more energy than would be released by ^{3}He fusion. Evaluations of the natural ^{3}He resources on earth indicate, thus far, that none provide ^{3}He in quantities required for a fusion power industry with a net energy gain.

The production of ^{3}He has been proposed via the radioactive beta decay of tritium (T), utilizing fission or fusion neutron sources to irradiate lithium and produce T. Alternatively, deuterium (D-D) fusion reactors have been suggested which produce neutrons, ^{3}He and T. The neutrons would be used to irradiate lithiun, forming T and all the T would be stored while it decays to ^{3}He. Such schemes require the storage of several tonnes of tritium in order to supply ^{3}He at the rate required for a 1000 MWe (D-^{3}He) fusion power plant. In addition, the breeder reactor structure would become radioactive from the neutronic irradiation. Large quantities of radioactive fuel and waste products are incompatible, however, with the introduction of clean fusion power.

The production of ^{3}He has been proposed, also, via the nuclear fusion reaction ^{6}Li(p,α)^{3}He. Unfortunately, the bremsstrahlung losses in an equilibrium plasma are exceedingly high so that the power consumption in such a breeder reactor may prohibit its usefulness.