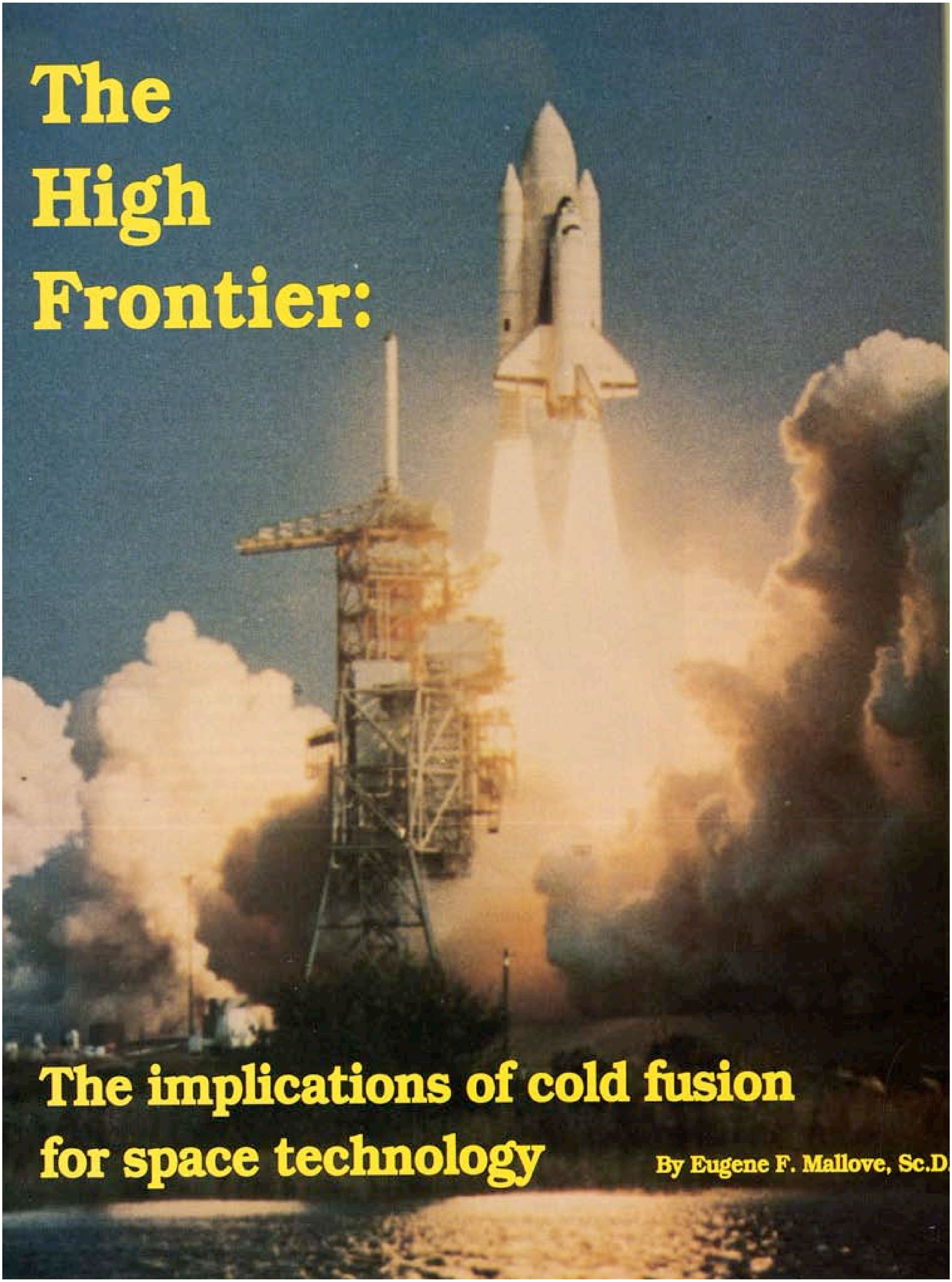

The High Frontier:
The implications of cold fusion for space technology
By Eugene F. Mallove, Sc.D.

Space Exploration: At the Turning Point

Space exploration is poised at a great turning point. There is a thirst for progress on the high frontier of space, but progress is limited. Economic and political conditions within the great spacefaring nations have seemed to make the more ambitious goals for expansion into space recede. Plans for establishing permanent inhabited laboratories on the Moon, and human missions to Mars have been delayed decades beyond when they were once expected to occur—the 1980s! Even the use of robotic probes to explore the solar system has faltered.

There is little doubt that the future of space exploration turns on the ability to develop less costly and more effective propulsion systems for lofting massive payloads into low Earth orbit (LEO) and for boosting spacecraft onto fast interplanetary trajectories. It now costs about $15,000 to $25,000 per kilogram to place payload into LEO. Furthermore, the fastest chemically-propelled trips to Mars require astronauts to be enroute for a large part of a year, with all the attendant risks of cosmic radiation and physiological effects of weightlessness, and with high-mass life-support requirements.

So, within the aerospace community there is a great hunger for new ways into space: single-stage-to-orbit craft, such as supersonic combustion ramjet (scramjet) hypersonic air-breathing vehicles (1) or more sophisticated rockets typified by the recent DC-X ("Delta Clipper-Experimental") prototype. Virtually all space exploration plans, however, are currently predicated on using cryogenic chemical propellants—H_2 and O_2—for launch from Earth's surface. These propellants were favored in the writings of the early space pioneers, so one might say that space technology has really not yet left the cradle.

Who can guess what strange roads there may yet be on which we may travel to the stars? —Arthur C. Clarke, "The Promise of Space," 1968

Did grandfather know best?

The great pioneers of space exploration, Robert H. Goddard, Hermann Oberth, and Konstantin E. Tsiolkovskii, believed—long before it was done—that humankind would use rockets to loosen the bonds of gravity, ascend to orbit, and travel to the Moon, Mars, and beyond. From its accelerated growth in the 1950s, space exploration has struggled with the severe limits that chemical energy imposes. Even within those constraints, much has been accomplished: communications, observation, and weather satellites are now integral to our lives; 12 men have traveled to the Moon's surface; people have lived in orbiting space stations; scientific probes have begun to explore all the planets except Pluto; there are astronomical observatories in space; we have learned to fly partially reusable spacecraft to and from low Earth orbit; and we have sent four robot emissaries on their way to interstellar space—the Pioneers and Voyagers.

Many other advanced propulsion concepts have been put forth in the past half-century, but none of these—including nuclear-powered rockets—have gone beyond the theoretical or experimental stage and come into common use. Now at the turning point in space exploration in the post-1989 "Cold Fusion Age," it should be possible to find ways to apply the spectacular energies in cold fusion phenomena to spaceflight. These cold fusion space technologies will not emerge overnight. They will be developed in parallel with the terrestrial energy and transportation sectors. As cold fusion begins to be applied vigorously to terrestrial needs during the next several years, aerospace applications should become irresistible.

The birth of nuclear spaceflight

Chemical reactions are typically millions of times less energetic per unit reaction than nuclear reactions, so it is not surprising that there have been efforts during the last four decades to apply nuclear energy to space propulsion in both studies and experimental development—conventional fission and fusion reactions. Even the early space pioneers recognized that nuclear energy might be extremely useful for space propulsion. The discovery of radioactivity in 1896, and the new understanding of the atom had a profound impact on the thinking of Goddard and Tsiolkovskii, among others. William Reupke has compiled a wonderful historical insight into the thinking of the rocket pioneers about atomic energy for spaceflight (2). Reupke points out that by 1903, the year of the Wright brothers' first powered flight, it was already established that the heating effect of radium was a million times greater than chemical reactions.

Even without a detailed understanding of radioactivity, the rocket pioneers were led to speculate about the role of this new energy for the future of space travel. Goddard (1882–1945) first held the opinion that "atomic energy" would be "impractical." Later, around 1907, he became more optimistic about atomic energy for spaceflight. Goddard had not yet examined the full potential of chemical rocket propulsion—specifically the importance of rocket staging—so in this era he was pessimistic about space travel unless atomic energy could be applied! Hence his 1907 statement, "In conclusion, then, the navigation of interplanetary space depends for its solution on the problem of atomic disintegration . . .Thus something impossible will probably be accomplished through something else which has always been held equally impossible, but which remains so no longer." [Shades of the cold fusion publishing problem (i.e. scientific censorship) of the past several years: Goddard's 1907 essay, according to W. Reupke, was rejected for publication by *Scientific American*, *Popular Science Monthly*, and *Popular Astronomy*!]

Goddard already had the idea that nuclear energy could be applied to spaceflight in two ways: (A) The direct expulsion of disintegration products to serve as a means of thrust, and (B) Using the heat of radioactivity to expel a larger mass of inert gaseous material. Both these methods were later extensively researched by fission nuclear propulsion people, beginning in the 1950s.

Konstantin Tsiolkovskii (1857-1935) did not incorporate atomic energy into his space travel speculation apparently until 1911-12, but when he did he was a great visionary. He conceived that atomic energy could be used to accomplish interstellar space flight, noting that first the radioactive disintegration rate would have to be increased! Tsiolkovskii soon became pessimistic about atomic energy, even as another rocket pioneer, the French aeronautical pioneer Robert Esnault-Pelterie (1881-1957) was becoming a proponent of the new nuclear energy in the 1920s. Goddard, of course, became completely immersed in his development of practical liquid-propel-

Photo left: Columbia lifts off from Cape Canaveral, 1981, in the second flight of a space shuttle. (Courtesy, NASA)

Adapted from a paper delivered by Eugene Mallove at the Fourth International Conference on Cold Fusion, Maui, Hawaii, December 1993.

The fundamental rocket equation is:

$M_o/M_f = \exp(DV/V_e)$, where M_o is the initial mass of the rocket loaded with propellant; M_f is the "burn out" mass when all propellant has been expended; Ve is the exhaust velocity, and ΔV is the total velocity change of the rocket (known as "Delta Vee" in the field of astronautics). The higher V_e, the smaller the mass ratio, M_o/M_f, needs to be. High mass ratio means, of course, that most of the initial mass of the rocket is propellant. This equation is for free space, ignoring the effect of gravity losses during the boosting phase, but it is a good approximation to overall system performance.

lant rockets. The other great astronautical pioneer, Hermann Oberth (1884-1989), considered nuclear energy in some of his correspondence in the 1920s, but was late in publishing anything about it (1954).

Nuclear-powered flight

The discovery of fission in 1938, and the advent of fission nuclear power in the 1940s led to a burst of enthusiasm to apply nuclear power to rocket propulsion, as well as to aircraft. So robust had the field of nuclear rocket propulsion become, that Bussard and DeLauer (3) published in 1965 what still remains the definitive text on the subject, "Fundamentals of Nuclear Flight." In an era of aerospace optimism, a vast technical literature emerged, which speculated how nuclear energy—fission, fusion, antimatter-matter annihilation, etc.—might eventually be applied to interstellar travel (4). In 1989, this author and colleague Gregory Matloff reviewed the entire field of nuclear propulsion and interstellar flight concepts in a book, "The Starflight Handbook," that is available to the wider public (5). So controversial was cold fusion then that the John Wiley & Sons editor rejected even a hint that cold fusion, if proved, might become applicable to spaceflight!

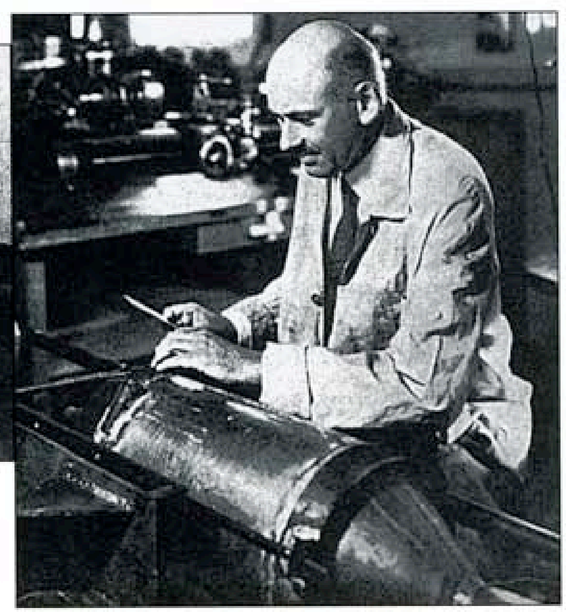
Nuclear rocket propulsion of the conventional variety came of age with the static testing of prototype engines in the 1960s. Billions of dollars were spent in the U.S. on the NERVA (Nuclear Energy for Rocket Vehicle Application) program. The aim was to permit a manned mission to Mars with a much smaller initial mass for the spacecraft than is possible with chemical propellants. The nuclear-propelled Mars mission would also have a substantially reduced interplanetary transit time. Conceptually, nuclear rocket engines are very simple. A compact fission reactor provides the thermal energy to heat hydrogen propellant, and expel the partially dissociated gas in a high temperature exhaust stream through a conventional DeLaval (converging and diverging) nozzle. The hydrogen propellant, initially a cryogenic liquid in a tank, is forced through the reactor so that there is intimate thermal contact between the reactor parts and the gas.

The NERVA-class prototype nuclear engines, which were ground-tested in the U.S. Southwest, had solid nuclear cores. That is, the uranium-carbide fuel elements were not allowed to get hot enough to melt. The range of performance of these solid core engines is in the range, Specific Impulse (Isp) = 800 - 1,100 seconds, whereas H_2-O_2 chemical propulsion has an Isp of about 460 sec. For those not familiar with rocket propulsion, specific impulse is a measure of the gross efficiency of a rocket engine—the impulse (force X time) imparted to the rocket per unit weight (mass X gravitational acceleration) of propellant expelled. The units of Isp are therefore seconds. It turns out that Isp (seconds) multiplied by g (9.8 m/sec^2) gives the exhaust velocity for that engine system. The higher the exhaust velocity, V_e, the higher the final velocity ("burn out" velocity) that a single stage rocket can reach with a fixed amount of propellant mass.

Now it is also possible to allow the nuclear core of the rocket to melt, leading to higher temperatures in the rocket pressure chamber, and a higher exhaust velocity. Of course, in such a liquid core rocket, a continuously fissioning (critical) geometry of the fuel-moderator combination must be maintained to allow the fission chain reaction to sustain. The general scheme proposed to do this, which has never been implemented in practice, is to spin up a vortex of uranium fuel-moderator droplets using streams of incoming hydrogen propellant. The hydrogen would come in intimate thermal contact with the extremely hot fuel droplets, and thus ultimately achieve a higher exhaust velocity. The vortex also helps to keep most of the nuclear material from being lost out the exhaust nozzle. An intermediate system between the solid core and the liquid core nuclear rocket is the colloidal core concept, in which solid particles of fissionable fuel several hundred microns in diameter are suspended in a rotating (or vortex-driven) fluidized bed.

In general, for thermal rockets—nuclear and chemical—the exhaust velocity is proportional to the square root of: (rocket chamber temperature)/(average molecular weight of the exhaust species). There is a great premium for elevated temperatures. Liquid core rockets that have been designed are in the Isp range, 1,300-1,600 seconds. It is possible to get even greater Isp in a fission rocket by running at such elevated temperatures that the fission core becomes a vortex of gaseous fuel. Projected Isp is in the range





Clockwise: German astronautical pioneer, Hermann Oberth.
Russian pioneer of astronautics, Konstantin Tsiolkovskii.
Dr. Robert H. Goddard works on one of his liquid-propellant rockets in his Roswell, New Mexico shop, 1935. (Courtesy Esther C. Goddard)

Cold fusion phenomena

1. Excess power production in D_2O-Pd/Pt (heavy water, palladium/platinum) electrochemical cells that exceeds megajoules per mole of cathode atoms when integrated over time, reaching in some cases thousands of eVs (electron volts) per atom on average. Excess heat emerges when D/Pd (deuterium/palladium) atom lattice loading ratio exceeds approximately 0.85.

2. Excess power bursts lasting for hours to days in D_2O-Pd/Pt electrochemical cells, during which the power ratio attains large values—on the order of 10.

3. Power densities in Pd and Pd-alloy cathodes that in some experiments already exceed 3.0 kilowatts per cubic centimeter.

4. Excess power production in ordinary water cells (which, of course, include trace levels of D) with nickel cathodes, Pt anodes, and electrolytes with salts such as as K_2CO_3, Rb_2CO_3, and Na_2CO_3— power ratios in such cells, which exceed 10 when input power is pulsed so as to give a low fractional duty cycle of input power. Integrated thermal excess power also exceeding many megajoules per mole of cathode, just as in heavy water cells. Excess power production does not require a lengthy lattice loading period, unlike in D_2O-Pd/Pt systems.

5. "Cold" tritium evolution, which is seen in both heavy water and ordinary water electrochemical cells. This tritium does not emerge at MeV energies, otherwise a considerable flux of 14 MeV neutrons from impact with D in the water and in the lattice would have been seen. Tritium levels are 10^6 -10^9 times attendant neutron production, in contrast to the 1/1 tritium/neutrons ratio in D-D hot plasma fusion. Tritium atoms are produced at up to 10^{11}/second, but usually at a rate much less than that.

6. Enhancement of excess heat production in ordinary water electrochemical cells, when employing 15 –25% heavy water.

7. Low levels of neutron emission from electrochemical cells at energies ranging from 2.45 MeV upward and at rates that are on the order of 10^{-23} neutrons per second per D-D pair in the metal cathode. Rates up to 10^3/second are observed—on occasion, 10^6/second briefly.

8. Production of excess thermal power in deuterium gas-loaded plates of palladium and in other alloys undergoing low voltage discharge phenomena. Input power amplification as excess power— ranging from two to five times input (e.g. Refs. 11,12).

9. The emission of neutrons, high energy charged particles, and gamma rays in low voltage gas discharge experiments with deuterated metals.

10. Transmutations of elements (e.g. Pd to Rh and to Ag, which are seen via gamma-ray signatures and short half-life measurements) and isotope shifts in Pd. Not only are these seen in electrochemical cold fusion cell cathodes, but also in gas discharge experiments (11).

11. Possible alkali element transmutations seen at high levels in light water cold fusion experiments, e.g. K to Ca or Rb to Sr in amounts reportedly commensurate with excess heat production (13).

12. Evolution of ^4He in heavy water electrochemical cells at levels reportedly roughly commensurate with excess heat (14, 15 and several papers delivered at the 1993 Maui ICCF4 conference).

13. The presence of ^4He at elevated levels inside spent Pd cathodes (16).

14. ^4He production correlated with heat release in deuterium-loaded Pd foils that experience discharge of D from the lattice—induced by an imposed ambient vacuum (17).

15. The generation of cold tritium in low-voltage gas discharge experiments (18).

16. Excess heat production in molten salt solutions of LiCl-KCl eutectic saturated with LiD. Elevated ^4He found in Pd electrodes in such cells (19).

17. Heat production beyond acoustic energy input from heavy water cells experiencing cavitation near metal surfaces. Concomitant ^4He production, proportional to energy release (20).

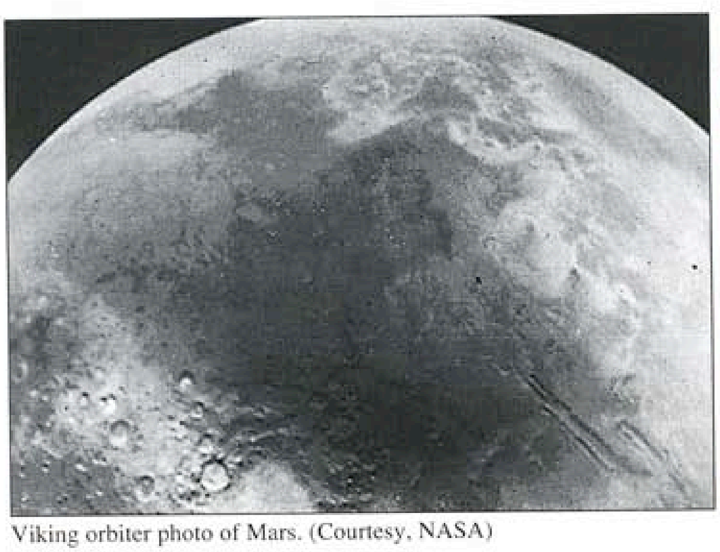
neered to make high thrust/weight rockets, cold fusion would still have enormous potential applications in space. Low thrust/weight ion engines, which have high specific impulse, need a low-mass source of electric power. Cold fusion-generated electricity would be ideal for this, reducing the mass and eliminating the shielding of a fission space power reactor. There are many other applications for cold fusion power in space infrastructure: power plants for lunar and Martian surface operations, power for satellite and space station operation in Earth orbit, and power for deep space probes, which now use solar cells and RTG's (radioisotope thermoelectric generators).

By the spring of 1991, the evidence for "cold fusion" was, in my view, overwhelmingly compelling (6). Now, it is 100 percent certain. The body of scientific evidence for these unexpected, astonishing, and allegedly "impossible" phenomena is now broad, deep, and expanding (7-10). Research has revealed what seems to be an entirely new realm of phenomena that has legitimately been called by some researchers solid state nuclear physics. The hundreds of researchers worldwide, who in 1989 entered—and remained with—the cold fusion field, have produced experimental results that give an extraordinary glimpse of the outlines of a new science. It is clear now that what Pons and Fleischmann discovered was actually only "the tip of the iceberg" of a broader class of phenomena.

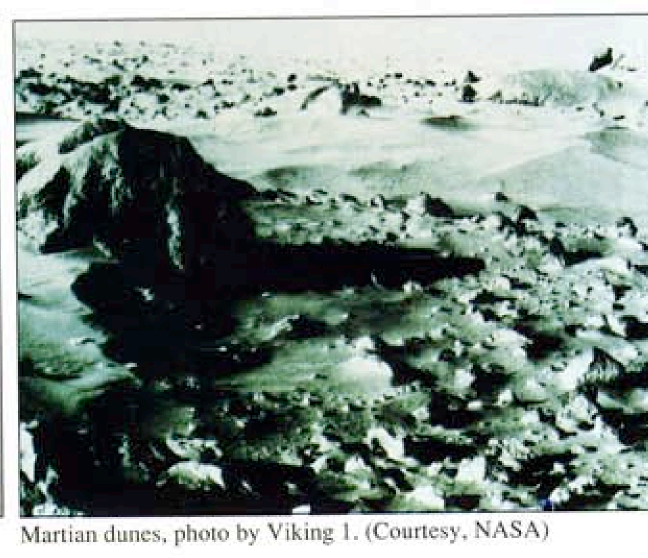
There exists at the moment no generally accepted theoretical framework to understand these phenomena, though many scientists have tried to "explain everything" on the basis of a single, unified theory. It is now clear that even without complete scientific comprehension of cold fusion phenomena, the levels of energy release (and their sustainability and repeatability in many experiments) are technologically useful.

In cold fusion, an enormous and bewildering array of phenomena need to be explained. Some of the most important aspects of the phenomena that need to be accounted for are listed in the accompanying sidebar above.

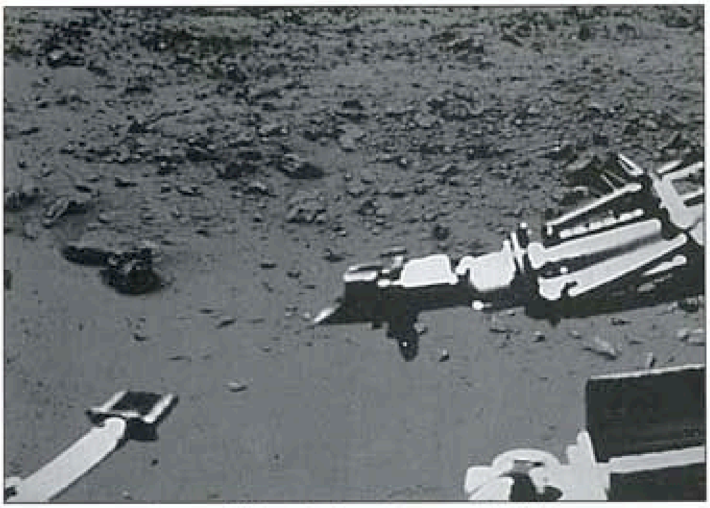
The most exciting potential of cold fusion reactions are the high thermal power densities that have already been observed by several researchers. Drs. Pons and Fleischmann (21) have demonstrated that a thermal power density of 3-4 kW/cm^3 of cathode material can be created in heavy water electrochemical cells. Kucherov et al (11) have observed similar power densities in metals in low



Viking orbiter photo of Mars. (Courtesy, NASA)



Martian dunes, photo by Viking 1. (Courtesy, NASA)



Martian scene from a Viking lander. (Courtesy, NASA)

Jupiter (Voyager photo). (Courtesy, NASA)

voltage discharge experiments with deuterium gas. Bush and Eagleton (22), using thin films of palladium to coat silver cathodes, have also observed spectacular power densities in the kW/cm^3 range. Moreover, several theorists and experimenters (e.g. Professor Peter Hagelstein of MIT and Martin Fleischmann) have suggested that cold fusion power densities may rise with increasing temperature.

Cold fusion—high thrust/weight rockets

Conventional solid core fission nuclear rockets have already reached an advanced state of development in both the U.S. and in the former Soviet Union (23-27). These rockets are high engine thrust/weight (T/W)—on the order of 3—at Isp of 800 seconds and above. In the period 1955-1973 the U.S. spent some $1.4 billion on solid core nuclear rockets—equivalent to a 1993 level of effort of about $10 billion. Some 20 ground tests were conducted before the program was terminated in the U.S.—not for technical reasons, but due to changed Federal budget priorities.

The highest power output of one of these solid core reactors reached 4,100 MW (megawatts) at a core temperature in the metal-clad fuel assemblies that reached 2,550° K. The test achieved a high thrust of 200,000 pounds at an Isp of 845 seconds. Demonstrations of multiple start-ups and shut-downs occurred, with thrusting duration exceeding one hour—more than adequate for missions contemplated. A mission to the Moon, for example, would require about 30 minutes of thrusting by a fission-nuclear shuttle leaving LEO, followed by 10 minutes of thrusting to achieve lunar orbit. In short, fission nuclear rocketry was developed to a high level, and then the civilian nuclear rocket program was junked in 1973 for reasons having nothing to do with problems with the technology. Military interest later emerged during the SDI (Strategic Defense Initiative) program. Interest in civilian nuclear rocket propulsion was born again with President Bush's Space Exploration Initiative (SEI).

It turns out that the average power density in these solid core fission reactors approached 3.0 kW/cm^3. (There are now reports that Russian nuclear rocket tests have achieved power densities as high as 40 kW/cm^3.) Since there was much zirconium carbide metal cladding and other structure, the uranium fuel itself did not reach such a high power density. It is remarkable, however, that 3.0 kW/cm^3 is roughly the power density that some cold fusion experiments have already achieved —in metal. The feasibility of a high performance cold fusion rocket may turn on whether a gas-metal electrical discharge system employing cold fusion surface reactions could operate at this high overall power density. By the suitable use of large surface area channels coated with thin films of Pd alloy material—a highly "fractalized" electrode system—such an average power density might be achieved. Whether the surface cold fusion reactions would sustain at the high pressures (gas densities) needed for high thrust/weight systems is an open question. Newly reported gas-phase cold fusion experiments at elevated temperature (over 400° C) with ceramic proton conductors and nick-

Jupiter's moon, Io (Voyager photo). (Courtesy, NASA)

Table 1.
Possible Specific Mass of CF Space Electric Power Generation
(Mass of total power system = K * Mass of Pd Electrodes)
(Assumption: 3.0 kW/cm^3 Pd power density)

K	e = 0.10 a (kg/kWe)	e = 0.30 a (kg/kWe)
10	0.4	0.13
100	4.0	1.3

Table 2.

Mission	Total Required ΔV (km/sec)	M_0/M_f for Isp = 460 seconds (H_2/O_2)
Ground to LEO (Low Earth Orbit)	7.9	5.8
Ground to Earth Escape	11.2	12
LEO to Geosynchronous Orbit	4.2	2.54
LEO to Moon polar region	6.2	3.95
LEO to Moon equator	5.6	3.46
LEO to Mars surface	4.2	2.54
LEO to Phobos	3.9	2.37
LEO to Jupiter orbit and return	64	1.5×10^6
LEO to Saturn orbit and return	110	3.9×10^{10}
Sun Impact (kill Earth's orbital velocity)	35	2,346

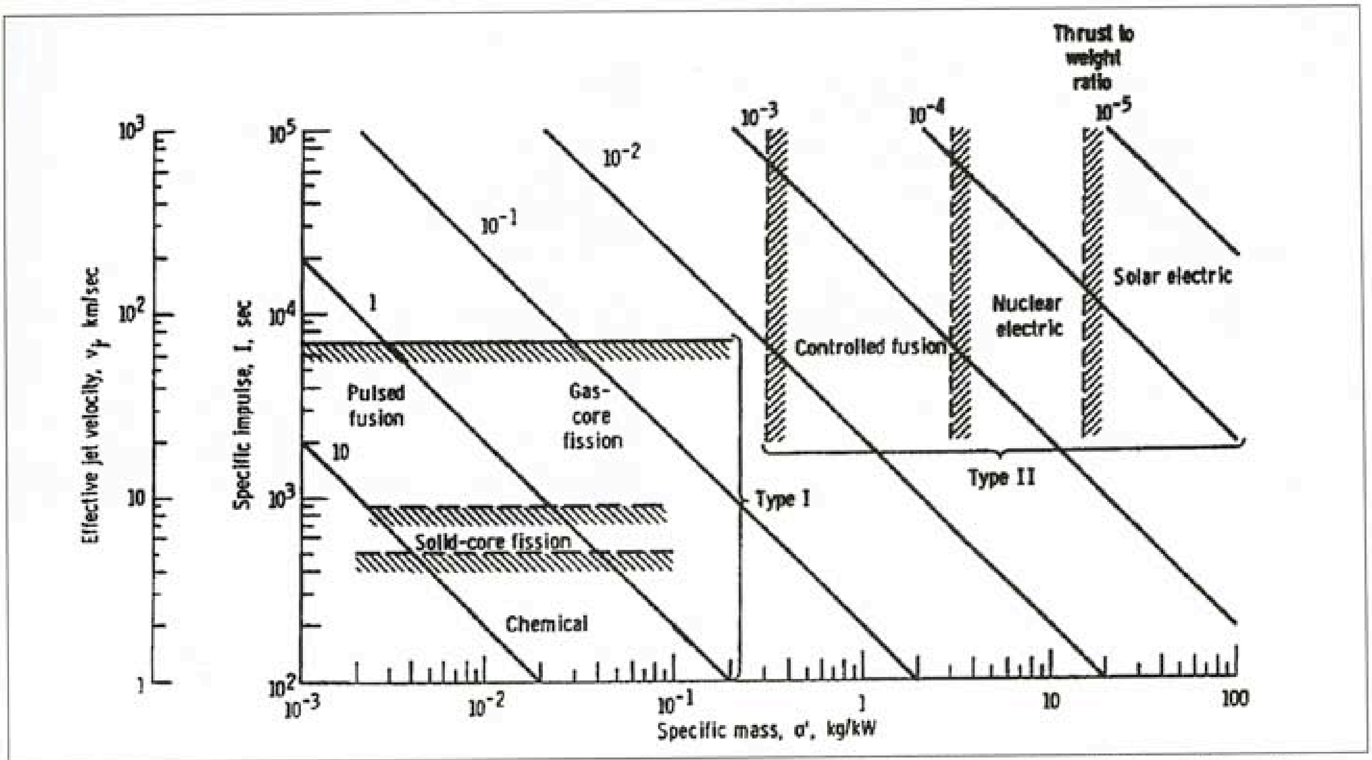


Figure 1. Rocket propulsion performance parameters. (Courtesy, NASA. From W.E. Moeckel, "Comparison of Advanced Propulsion Concepts for Deep Space Exploration," NASA TN D-6968, September 1972.)

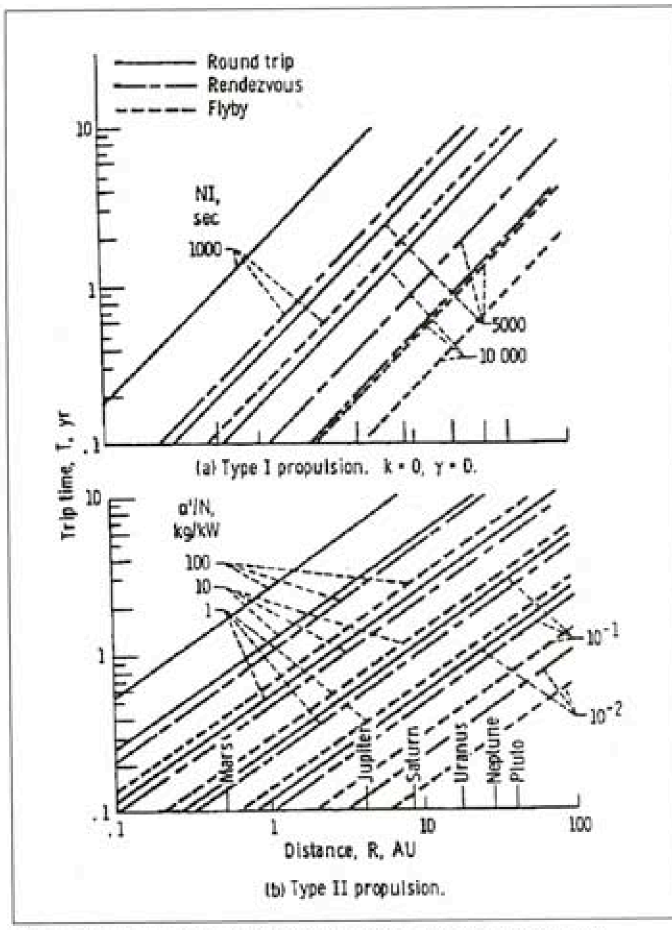


Figure 2. Interplanetary distance versus trip time. (Courtesy, NASA. From W.E. Moeckel, "Comparison of Advanced Propulsion Concepts for Deep Space Exploration," NASA TN D-6968, September 1972.)

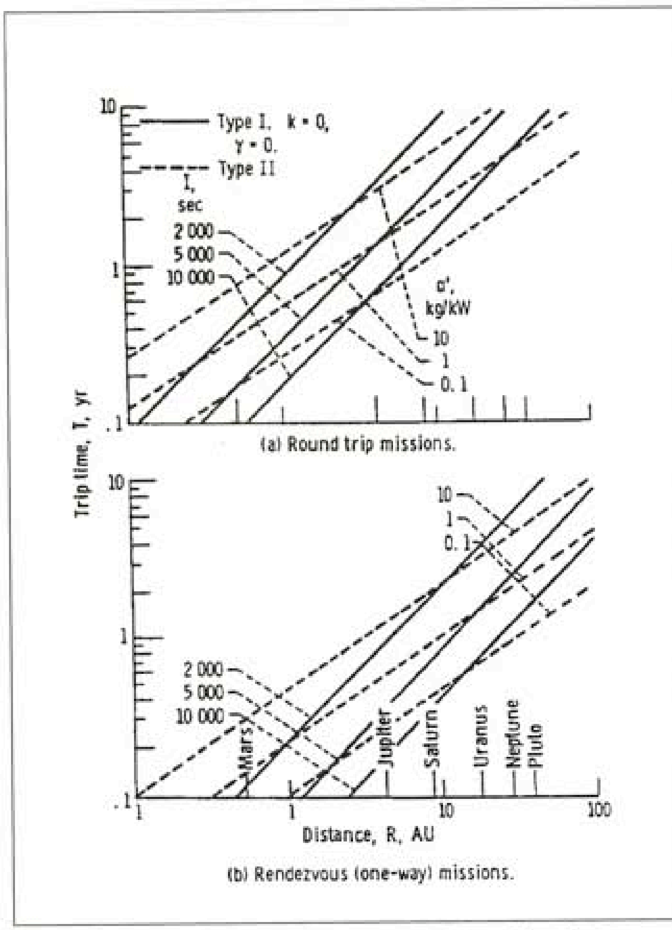


Figure 3. Comparison of Type I and Type II Propulsion for Planetary Distances. N = 1. (Courtesy, NASA. From W.E. Moeckel, "Comparison of Advanced Propulsion Concepts for Deep Space Exploration," NASA TN D-6968, September 1972.)

el catalysts suggests we should be very optimistic.

Perhaps the particle bed reactor or colloidal core geometry would be useful in high T/W cold fusion engines. Colloids suspended in a gas flow offer the highest surface area per unit volume of active material, and thus facilitate better heat transfer to the propellant. It won't be much longer before cold fusion research proceeds in the direction of such particle beds for terrestrial power generation, so the foundation for cold fusion space propulsion may be laid through these more mundane applications. Perhaps colloid cold fusion reactors would not require electrical gas discharge phenomena to trigger surface reactions. Some researchers in the cold fusion field have speculated that deuterium-loaded metal structures (perhaps clad with ceramics), once triggered, could be made to remain at high temperatures for prolonged periods without electric stimulation. Evidence that this will be possible has been mounting.

Jupiter's moon, Europa. Beneath the surface lies an ocean of water according to some astronomers. (Voyager photo). (Courtesy, NASA)

The problems of fission nuclear power for spaceflight would be significantly reduced if there were no radioactive exhaust or radiation shielding problem. Therein lies the basic appeal of cold fusion . . .

At least one experimentalist and theorist, A. Takahashi of Osaka University, has suggested that the upper limit of the power density of cold fusion reactions has not been reached. He suggests that one category of his deuterium multi-body cold fusion reactions may allow power densities as high as 1 megawatt/cm^3—"well beyond the explosion condition," he adds (28).

Cold fusion—ion engines

Ion engines, which are high Isp and low thrust to weight (T/W = 10^{-4}) engines, have always been appealing to space mission planners. Their specific impulse range is 5,000–100,000 seconds. Ion engines have already been built in the Isp = 5,000 second range, and tested in space vacuum simulators for many thousand hours. Several engine tests have been done in Earth orbit. Basically these engines employ atoms such as mercury, cesium, argon, or xenon, which are first ionized and then accelerated in high voltage electrical fields to form a collimated thrust beam. The beam is kept electrically neutral by recombining the atoms downstream with the stripped electrons.

Due to low T/W, ion engines are only suited for operation in orbit, never for launch from the surface of high gravity celestial bodies. The thrust of ion engines that have already been built are rated in the 10–200 milli-Newton range—minute compared to chemical rockets, but at much higher Isp—3,000–5,000 seconds. There is another disadvantage, which is somewhat compensated for by the high Isp. It may take months for an ion engine-powered vehicle to spiral out of the "gravity well" of a planet on an escape trajectory. This illustrates the well-known penalty in astronautics for not achieving orbital energy or escape energy impulsively. When a high T/W rocket fires, it accomplishes the required velocity change within minutes, not months. Gravity does not have time to retard the vehicle much. Not so for ion engine trajectories, which are slow anyway due to to low inherent acceleration.

Ion engines require a source of electrical power, and it is here where cold fusion comes in. Cold fusion would not be aimed at improving the ion engine itself, though some might well consider trying to develop charged particle-emitting cold fusion reactions for this purpose! Rather, cold fusion would better the characteristics of the ion engine's electrical power supply. Present power supplies contemplated for deep space ion-engine missions are fission nuclear reactors. This form of propulsion has thus become known as Nuclear Electric Propulsion (NEP). In the U.S.

Figures left: In Figure 1., reproduced from the Moeckel report, we see the relation of Isp, specific mass, and thrust/weight. Specific mass in Figure 1. is the propulsion system mass ratioed to the exhaust beam power, which for the case of ion engines (NEP) is roughly the specific mass of the electrical power system—so both high and low T/W systems are placed on the same basis of comparison. Type II systems, as defined by Moeckel, are not Isp-limited. Their Isps are high enough to keep mass ratios down, which is their main advantage. Type-II systems are low T/W—NEP, solar electric, and controlled hot fusion rockets. They become better performing—have higher T/W—with better (lower) specific mass. Type I propulsion systems are limited by attainable Isp, but they have high T/W. This allows them to depart the surfaces of high-gravity celestial bodies like Earth. Chemical propulsion systems have engine T/Ws in the 30-60 range, while fission nuclear rockets have engine T/Ws around 3 for solid core and 0.3 for gas core. Type-I engines are not limited by specific mass. We expect that cold fusion Type-I engines could be developed with a higher engine T/W than fission nuclear rockets.

Cold fusion propulsion systems will either be: (A) Like the solid core fission Type-I system, equalling or exceeding the solid core fission rocket in Isp and perhaps T/W, or (B) like the NEP (fission nuclear electric) Type-II system, perhaps being better in specific mass by a factor of 10 or more.

Figure 2., also from the Moeckel report, illustrates how Type-I and Type-II systems compare in interplanetary trip times for round-trip, rendezvous, and flyby missions to planets from Mars to Pluto [Note: In Figure 2. NI is Isp X number of rocket stages, N.]. Figure 3. from Moeckel portrays the same information as Figure 2., but allows more direct comparison of Type-I and Type-II systems for the round-trip and rendezvous missions.

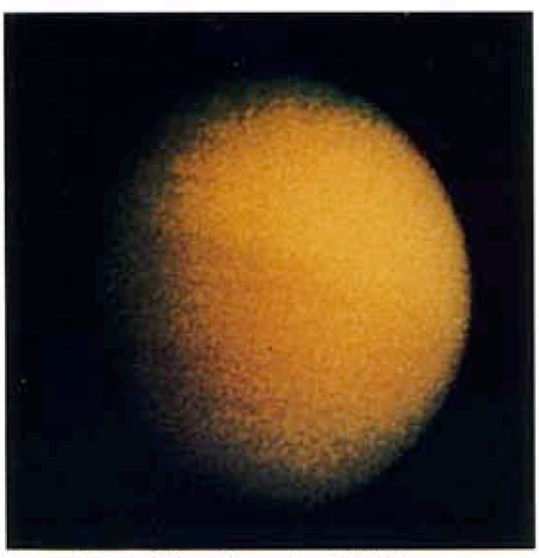
The conclusion for cold fusion rocketry is not different than for the Type-I and Type-II conventional systems. Acceptable trip times define the Isp (for Type-I) or specific mass (for Type-II) required to perform the various missions. Simply construct a horizontal line at the acceptable trip time to define the system performance required for the mission. Figure 3. presents the data more conveniently for determining the cross-over points where Type-I systems begin to perform more poorly mission time-wise than Type-II systems. The cross-over point for round-trip missions is at about the distance of Jupiter. The cross-over point for planet rendezvous missions lies beyond Saturn.

Saturn, July 21, 1981 (Voyager photo). (Courtesy, NASA)

the planned space reactor, "SP-100," is a molten lithium metal-cooled uranium reactor. Thermal energy of 2.5 megawatts (MW) would be converted thermoelectrically to 100 kW of electricity. Much more power than this (several to tens of MW) would be required to boost tens of metric tons to Mars. A 5-10 MW power unit is considered ideal to be clustered for Mars and lunar missions.

The key parameter defining the performance of the electrical system is its specific mass, a, the "kilograms per kilowatt" of the system. The SP-100 has a design goal of about a =10 kg/kWe (kWe refers to kilowatts of electricity produced, to distinguish from kW of raw thermal power). Present capability is about a = 50 kg/kWe. Palladium cold fusion cathodes have already demonstrated 3 kW/cm^3 thermal output, or 250 kW/kg. Using this basic thermal output, we can postulate various factors by which the mass of the remaining components of a thermal-to-electric conversion system might exceed the mass of palladium. Then find the specific mass of the power system for two reasonable thermal-to-electric conversion e efficiencies, e,10% and 30% (see Table 1.)

These numbers bracket a range of possible CF electrical power system designs, perhaps using either thermoelectric power conversion or a closed-loop heat engine cycle, both with a required space radiator. Since there will be no nuclear shielding requirement, and a CF reactor is expected to be of generally lighter construction than a fission reactor, an a in the range 1.0 to 4.0 (K = 100) seems realistic—a factor of 10 or more better than current technology.



Saturn's moon Titan, November 9, 1980 (Voyager Photo). (Courtesy, NASA)

Space missions and performance parameters

Despite slumping fortunes of the global space effort, the Moon and Mars still beckon powerfully. Do not assume, however, that these are the only worthy destinations for science and commerce. Dana Rotegard (29) and others in the space industrialization movement have pointed to the utility and accessibility of asteroids and the moons of Mars, Phobos and Deimos. In the energy required to perform missions to them, they are more accessible than our own Moon! Rotegard made a point about the valuable platinum group metals (PGM), including palladium and platinum, which are thought to be in high concentration on asteroidal-type chondritic bodies, such as Phobos and Deimos. It is not certain that palladium and platinum will become dominant ingredients in cold fusion technologies, but if they do, mining Phobos and Deimos and other asteroids for PGMs could become a high-priority space mission. The Earth's crust is not rich in the PGMs, and the 21st century may see industrial shortages if the extraterrestrial resource is not developed.

Space missions are characterized by the ΔV and payload mass required to carry them out. Table 2. presents typical ΔVs for a variety of space missions (data compiled, in part, by Rotegard). These give an idea of the magnitude of ΔVs for within the solar system. These are typically minimum ΔVs. Higher performance rockets capable of imparting higher ΔVs could drastically cut trip times. (See Table 2.)

The payload ratios for a single-stage configuration in the third column of Table 2. show how incompatible chemical rocketry is for missions to the outer solar system. The mass ratios become absurdly high. (Those outer planet missions that have been carried out to date have relied heavily on staging and gravity-assist planet swing-by trajectories.) That is why high Isp ion engines are favored for these deep space missions.

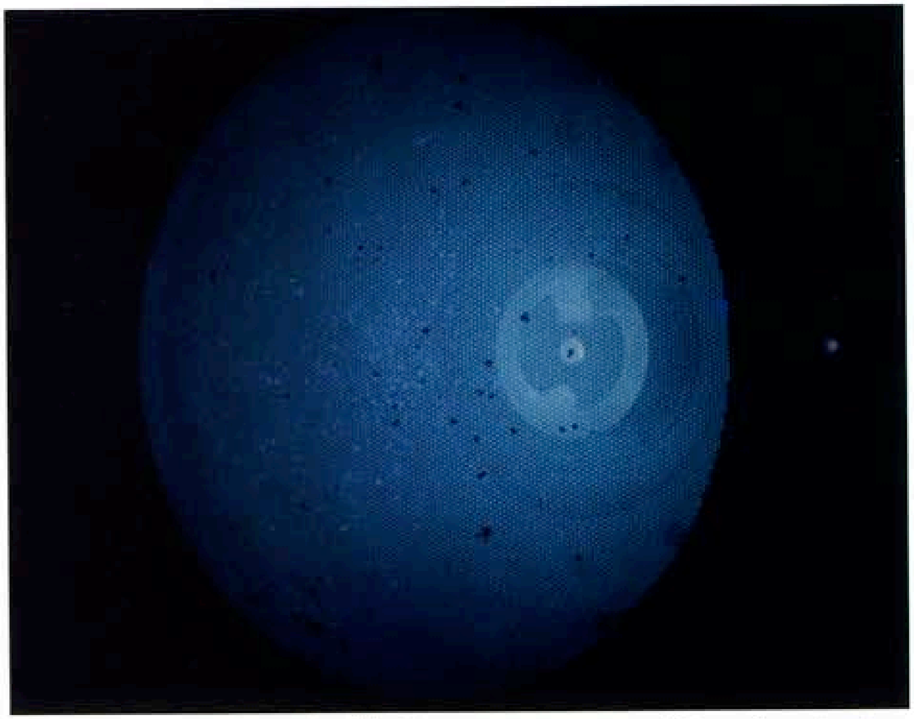
Comparing the mission performance of propulsion systems with different Isps and T/Ws was put on a firm footing by W.E. Moeckel in a classic NASA technical report in 1972 (30). It is worth reproducing several figures from the Moeckel study. By using free-space equations (ignoring lift-off from planets) and several simplifying equations, he put comparative propulsion system performance on a sound footing. Edward Teller et al (31) performed a similar, though much abbreviated analysis, which also relied on the utility of free-space approximations. This was in the context of analyzing a non-tokamak hot fusion rocket engine using D-^{3}He fuel. (Aneutronic hot fusion engines may, indeed, have a role in space exploration, though the technology required to develop them likely would be very difficult and expensive. This area might be a suitable research activity for people working today on hot fusion tokamak systems, after the expected termination of those programs.)

Cold fusion—space power generation

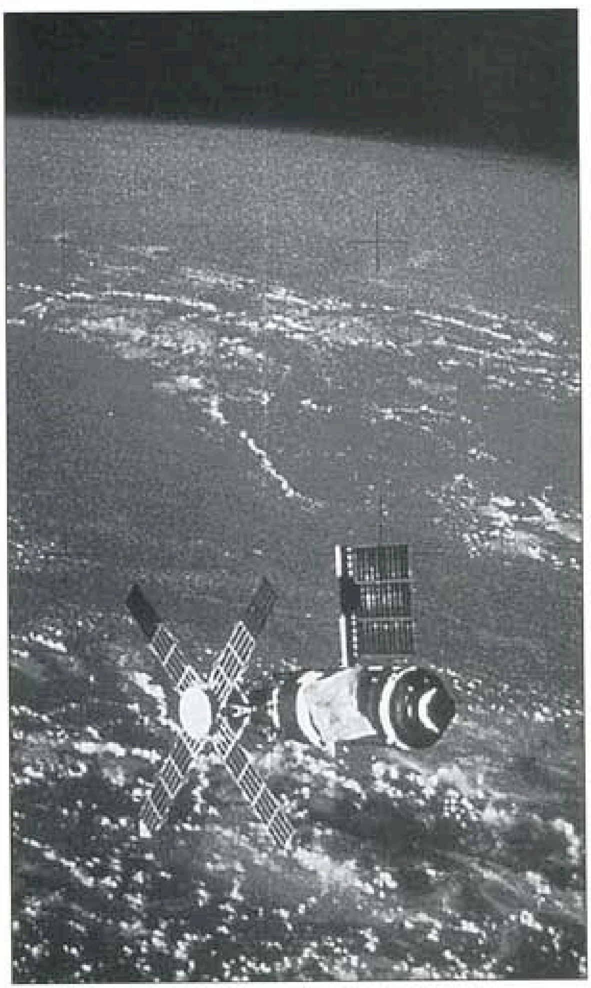
The advent of cold fusion power probably means the end of at least one formerly very creative and attractive proposed space project: the use of so-called "Satellite Solar Power" (SPS) to convert light from the Sun to electricity. The proposal was to set up vast acreage of photovoltaic cells in geosynchronous orbit, and beam multi-gigawatts of microwave energy down to collecting antennas on the ground. The ground-based multi-acre dipole antenna farm would convert the tight beam of microwave energy to electricity for the power grid. This concept was put forth in the late 1960s by Peter Glaser of the Arthur D. Little company.

With abundant energy available from water on Earth, there will be no motivation or reason to construct gigantic solar energy collectors in space. The late physicist Gerard K. O'Neill, author of the pre-Cold Fusion Age books, "The High Frontier" and "2081: A Hopeful View of the Human Future," was a leading proponent of SPS. These books illustrate that the projections of a far-seeing prophet of technology like O'Neill could be completely upset by an unsuspected discovery like cold fusion.

Though power beamed down to Earth need no longer be sought, the need for electric power and heating for space stations and other spacecraft has not disappeared. Compact electric generators based on cold fusion should become standard power equipment for spacecraft.



An electric propulsion ion engine firing in a space vacuum test cell. Ion engines, already perfected in laboratory testing, require only a suitable source of electric power to operate in space. Cold fusion reactors, compact and light weight, will be that source.



Ill-fated U.S. Skylab "space station," with solar panels visible. (Courtesy, NASA). A cold fusion electric power subsystem would eliminate these unwieldy panels.

Lunar and Martian surface operations will also require cold fusion electrical power and heating. Also, industrial in-situ processing of extraterrestrial materials will require electrical power and heat.

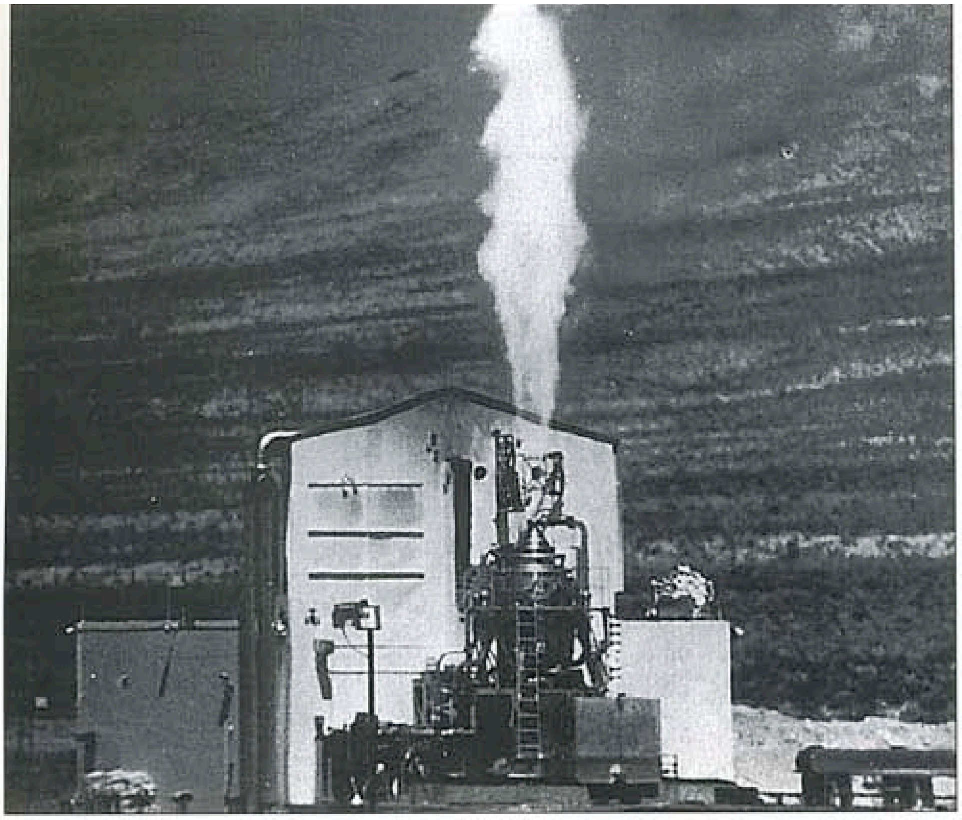
Space mission planners have typically discussed using arrays of solar energy collectors to power operations on planetary surfaces. Solar power is a very weak proposition for Mars, given that solar illumination at the Mars distance from the Sun is about one-half that at Earth. One study projects the required collecting area for a 10-person base on Mars (32). The designers concluded that the base would require about 10^{12} joules/Mars year for an average continuous power of 20 kilowatts. For high Martian latitude, this would be provided by an array of Sun-tracking solar cells 8,760 m^2 in area, with a mass of 113,900 kg. Small cold fusion generators in this power range for terrestrial home use, which are now being developed, could provide the Mars base power for a minute fraction of that mass.

J.R. French (33) has discussed the great benefits for Mars missions of extracting rocket propellants from the thin (mostly CO^2) Martian atmosphere. Mars air is taken in, compressed, and the CO^2 separated. A thermal decomposition unit then manufactures bi-propellant rocket fuel, liquid CO and liquid O^2. (Others suggest carrying some liquid hydrogen to Mars and using it to create methane and oxygen rocket bi-propellant from the Martian atmospheric CO^2). This permits launching a much smaller mass toward Mars on early missions, because the propellant for the entire mission is not carried. Using small cold fusion power sources to produce this propellant will make its use even more attractive for surface operations—and for the return to Earth. One can readily imagine roving vehicles and Mars aircraft powered by cold fusion motors or the cold fusion-manufactured propellant.

Cold fusion energy will reduce the launch mass of on-board chemical consumables needed for Mars exploration. It will eliminate the hazards and the radiation shielding requirements of proposed Mars mission fission reactors. There is no question that cold fusion will make Mars exploration much more attractive. Since the time frame for Mars missions is early 21st century, it is likely that the very first human explorers of the planet will rely on cold fusion power generation.

Far out possibilities?

The advent of a radical departure from a reigning scientific or technology paradigm rarely comes easily. For nearly five years since its announcement, cold fusion has been both mocked and ignored—despite the immense technological implications of the phenomenon. The Wright brothers experi-



The KIWI-A fission nuclear rocket being test-fired with hydrogen propellant in July 1959. (Courtesy, NASA)

enced similar difficulties convincing the world that their powered aircraft was real—even though they were flying near an interurban railway for all the world to see at Huffman prairie near Dayton, Ohio (34). The *New York Times* did not pick up on the story. It took nearly five years from December 17, 1903, at Kitty Hawk to the Wrights' triumphant demonstration at Fort Myer, Virginia, in September 1908, to end the dispute.

Robert H. Goddard's work on spaceflight was also attacked by the "establishment" in a 1920 editorial in the *New York Times*, which stated: "That Professor Goddard with his 'chair' in Clark College and the countenancing of the Smithsonian Institution does not know the relation of action to reaction, and of the need to have something better than a vacuum against which to react—to say that would be absurd. Of course, he only seems to lack the knowledge ladled out daily in high schools . . ." The *Times* formally retracted this editorial after the Apollo 11 lunar landing in 1969.

Cold fusion pioneers Drs. Pons and Fleischmann were attacked in an April 30, 1989 *New York Times* editorial in even sharper terms than the paper had used against Goddard. The *Times* editorial said, "[the University of Utah] may now claim credit for the artificial heart horror show and the cold fusion circus, two milestones at least in the history of entertainment, if not science . . . Given the present state of evidence for cold fusion, the government would do better to put the money on a horse." All this, while still acknowledging that there might actually be something to cold fusion after all! One wonders when the *Times* will get around to retracting this editorial *faux pas*.

Given the surprises of the past five years, may we expect other shocks in the cold fusion field that would affect space technology? Very likely so.

One such new direction might emerge (I definitely reserve judgment on this shocking claim, but insist that it must be investigated.) from the extraordinary allegations and demonstrations of an eccentric American inventor, Mr. Stanley A. Meyer of Grove City, Ohio. Meyer claims to have discovered a process whereby a stochiometric mixture of hydrogen and oxygen is liberated from ordinary water with far less energy than normal electrolysis. Meyer has described his "Water Fuel Cell" apparatus in a series of U.S. patents, the most important of which appear to be U.S. #4,798,661 and U.S. #4,936,961 (35,36). In fact, Meyer claims his process to be so potent, that he has managed, he says, to power a small dune buggy (with a 47 HP VW engine) by combusting the stochiometric H_2-O_2 gas. The gas is generated, he claims, with a small amount of power derived from the vehicle's alternator, which is fed to his patented circuitry.

So shocking are these Meyer claims that no one even in the open-minded cold fusion field would have taken them seriously, had not retired Admiral Sir Anthony Griffin of the Royal Navy not vouched for them as an eye-witness (37,38). Several groups are now at work attempting to replicate and understand the ramifications of the Meyer apparatus. At least one respected theorist in the cold fusion field has suggested that Meyer's process involves the nuclear-induced splitting of the oxygen-hydrogen bonds in water.

Meyer apparently has developed a resonant circuit with inductive and resistive elements that applies unipolar pulsed power at high voltage and low current to a "water capacitor" stainless steel electrodes with ordinary water between them. He claims non-Faradaic dissociation of the water in his cell, i.e., dissociation of water into H_2 and O_2 not proportional to current passing through the water (which requires no current-carrying salt to operate). Meyer is not trained in the mold of an academic scientist, so he has not published scientific data that would establish these claims firmly. He has not published the specific power ratio that his resonant apparatus can achieve—the combustion energy of the H_2-O_2 versus the input power. Nonetheless, his demonstrations, which have been witnessed by several engineers and scientists, are impressive.

Could Meyer have stumbled onto another strange aspect of "cold fusion?" He, himself, suggests that he has discovered a way to tap "zero point energy." Several researchers in the cold fusion field who are now trying to verify the Meyer claims hypothesize that a low-level endothermic nuclear process may be responsible for breaking the hydrogen-oxygen bonds. Consider this question. Which is less "believable" a priori: (A) the occurrence of radiationless nuclear-derived heating of metallic lattices, or (B) radiationless breaking of chemical bonds via nuclear reactions? We now know that (A) is true—at least for some cold fusion experiments. It doesn't seem such a stretch that (B) could be true as well, but the evidence, though tantalizing, is still not in.

Perhaps the biggest near-term boost that cold fusion could give to space exploration would be a large shot of adrenaline to terrestrial national economies.

The Meyer Process, if real, would have extraordinary implications for space travel. It would be possible to develop true "water rockets"—rockets that would use liquid water as propellant, and yet achieve the high specific impulse of cryogenic H_2-O_2. This would lead to large savings in the equipment currently required to handle liquid H_2 and liquid O_2: cryogenic turbopumps, sophisticated and separate tankage, etc. Where now safety issues at launch (e.g. the U.S. Space Shuttle) are extraordinary, the hazards of launching a water rocket would be minimal. This could lead ultimately to simple, inexpensive, and widespread boosting to LEO and beyond. Furthermore, since Mars, comets, Jupiter's moon Europa and perhaps some subterranean or polar regions on the Moon already have significant stores of water, the water fuel would already be widely distributed in the solar system.

So, for the ultimate opening of the High Frontier, let us hope that a second "miracle" has really come out of Ohio—that Stanley Meyer has indeed followed in the footsteps of the Wrights. However, the aerospace community should not wait for Meyer to be more open about his work. The implications of cold fusion for space technology are already revolutionary enough. Would-be space pioneers will doubt them at their own peril.

Perhaps the biggest near-term boost that cold fusion could give to space exploration would be a large shot of adrenaline to terrestrial national economies. The emerging technological revolution cold fusion will unleash will cause tremendous dislocation, as societies try to adjust to the beginning of the end of the Fossil Fuel Age. But the cold fusion era should also create much new wealth in emerging industries. An era of technological optimism and economic revival will, one hopes, find a place for greatly expanded space exploration. When historians look back at the strange 40-year gap that will separate the lunar exploration of 1968-1972 from the Mars missions and Moon trips of the early 21st century, they may conclude that these had to await cold fusion.

'In conclusion then, the navigation of interplanetary space depends for its solution on the problem of atomic disintegration . . . Thus, something impossible will probably be accomplished through something else which has always been held equally impossible, but which remains so no longer.'
—Robert H. Goddard, October 3, 1907

References:

1. National Commission on Space, "Pioneering the Space Frontier: The Report of the National Commission on Space," New York, Bantam Books, 1986, pp.112–115.
2. William A. Reupke, "The Rocket Pioneers and Atomic Energy," *The Journal of the British Interplanetary Society*, Vol.45, No.7, July 1992, pp. 297-304.
3. R. W. Bussard and R.D. DeLauer, "Fundamentals of Nuclear Flight," McGraw-Hill, New York, 1965.
4. E. F. Mallove, Forward, R.L., Paprotny, Z., and Lehmann, J., "Interstellar Travel and Communication: A Bibliography," a special issue of *The Journal of the British Interplanetary Society*, Vol.33, No.6, June 1980, 201-248, the complete issue (and subsequent updates in *JBIS*).
5. E. F. Mallove and Gregory Matloff, "The Starflight Handbook: A Pioneer's Guide to Interstellar Flight," John Wiley and Sons, New York, August 1989.
6. E. F. Mallove, "Fire from Ice: Searching for the Truth Behind the Cold Fusion Furor," John Wiley & Sons, 1991.
7. Edmund Storms (Los Alamos National Laboratory), "Review of Experimental Observations About the Cold Fusion Effect," *Fusion Technology,"1991, Vol.20, December 1991, pp.433-477.*
8. *T. Bressani, E. Del Giudice, and G. Preparata (editors), "The Science of Cold Fusion: Proceedings of the II Annual Conference on Cold Fusion," June 29–July 4, 1991, Como, Italy, published by* the Italian Physical Society,*Bologna, Italy, 1991, (528 pages).*
9. *Hideo Ikegami (editor), "Frontiers of Cold Fusion, Proceedings of the Third International Conference on Cold Fusion," Nagoya, Japan October 21–25, 1992), National Institute for Fusion Science, Nagoya 464-01, Japan (698 pages).*
10. *Peter L. Hagelstein, "Summary of the Third International Conference on Cold Fusion in Nagoya," MIT Research Laboratory for Electronics report, January 1993.*
11. *A.B. Karabut, Ya.R. Kucherov, and I.B. Savvatimova, "Nuclear product ratio for glow discharge in deuterium,"* Physics Letters A., *Vol.170, November 9,1992, pp.265-272.*
12. *Jaques Dufour, "Cold Fusion by Sparking in Hydrogen Isotopes,"* Fusion Technology, *Vol. 24, September 1993, pp.205-228.*
13. *Robert T. Bush and Robert T. Eagleton, "Experiments Supporting the Transmission Resonance Model for Cold Fusion in Light Water: I. Correlation of Isotopic and Elemental Evidence with Excess Heat," pp. 405-408, Frontiers of Cold Fusion, Proceedings of the Third International Conference on Cold Fusion, ibid.*
14. *B.F. Bush, J.J. Lagowski, M.H. Miles, and G.S. Ostrom, "Helium Production During the Electrolysis of D2O In Cold Fusion Experiments,"* J. Electroanalytical Chemistry, *Vol. 304, 1991, pp.271 -.*
15. *M. H. Miles, R.A. Hollins, B.F. Bush, J.J. Lagowski, and R.E. Miles, "Correlation of excess power and helium production during D2O and H2O electrolysis using palladium cathodes,"* J. of Electroanalytical Chemistry, *Vol. 346, 1993, pp.99–117.*
16. *Chung-Ching Chien, Dalibor Hodko, Zoran Minevski, and John O'M Bockris, "On an Electrode Producing Massive Quantities of tritium and helium,"* J. Electroanalytical Chemistry, *Vol. 338, 1992, 189-212.*
17. *E. Yamaguchi and T. Nishioka. "Direct Evidence for Nuclear Fusion Reactions in Deuterated Palladium," pp.179-188, Frontiers of Cold Fusion, Proceedings of the Third International Conference on Cold Fusion, ibid.*
18. *T.N. Claytor, D.G. Tuggle, and S.F. Taylor, "Evolution of Tritium from Deuterided Palladium Subject to High Electrical Currents," pp.217-229, Frontiers of Cold Fusion, Proceedings of the Third International Conference on Cold Fusion, ibid.*
19. *Bor Yann Liaw, Peng-Long Tao, and Bruce E. Liebert, "Helium Analysis of Palladium Electrodes After Molten Salt Electrolysis,"* Fusion Technology, *Vol.23, January 1993, pp.92-97.*
20. *Roger Stringham, "Cavitation Induced Micro-Fusion," paper presented at the Fourth International Conference on Cold Fusion, Maui, December 6-9, 1993.*
21. *Martin Fleischmann and Stanley Pons, "Calorimetry of the Pd-D_2O system: from simplicity via complications to simplicity,"* Physics Letters A, *Vol.176, May 3, 1933, pp.118-129.*
22. *Robert T. Bush, "Cold 'Fusion: The Transmission Resonance Model Fits Data on Excess Heat, Predicts Optimal Trigger Points, and Suggests Nuclear Reaction Scenarios,"* Fusion Technology, *Vol.19, March 1991, pp.313-356.*
23. *S.K. Borowski, E.A. Gabris, J. Martinell, , R.J. Bohl, W.L. Kirk, R.R. Holman, D. Budden, A.E. Mensing, T.S. Latham, G.A. Beale, and T.J. Lawrence, "Nuclear Thermal Rockets: Next Step to Space, a collection of articles by groups of the authors, Aerospace America, June 1989, pp.16-29.*
24. *S.K. Borowski, J.S. Clark, M.C. McIlwain, and D.G. Pellaccio, "Nuclear Thermal Rockets: Key to Moon-Mars Exploration," Aerospace America, July, 1992, pp.34-37, 48-49.*
25. *Milton Klein, "Nuclear Rocket Propulsion—The Past Is Prelude,"* Fusion Technology, *Vol. 20, December 1991, pp.693-697.*
26. *R.J. Bohl, F.P. Durham, and W.L. Kirk, "Nuclear Rocketry Review,"* Fusion Technology, *Vol. 20, December 1991, pp.698-709.*
27. *O.C. Jones, "Rotating Fluidized Bed Reactor for Space Power and Propulsion: A Status Report,"* Fusion Technology, *Vol.20, December 1991, pp.741-746.*
28. *A. Takahashi, "Excess Heat and Nuclear Products by D_2O/Pd Electrolysis and Multibody Fusion,"* International Journal of Applied Electromagnetic Materials, *Vol. 3, 1992, p.221.*
29. *Dana R. Rotegard, "The Development of Space: The Economic Case for Mars," The Case for Mars III: Strategies for Exploration— Technical, Vol. 75, Technology Series, Ed. by Carol Stoker, American Astronautical Society, 1989.*
30. *W.E. Moeckel, "Comparison of Advanced Propulsion Concepts for Deep Space Exploration," NASA Technical Note TN D-6969, Lewis Research Center, September 1972.*
31. *Edward Teller, A.J. Glass, T. Kenneth Fowler, Akira Hasegawa, and J.F. Santarius, "Space Propulsion by Fusion in a Magnetic Dipole,"* Fusion Technology *Vol. 22, August 1992, pp.82-97.*
32. *David H. Atkinson and Owen Gwynne, "Design Considerations for a Mars Solar Energy System,"* Journal of the British Interplanetary Society, *Vol.45, No.5, May1992, pp.183–194.*
33. *J.R. French, "Some Unconventional Approaches to the Exploration of Mars,* Spaceflight, *Vol. 33, February 1991, pp.62-66.*
34. *Fred C. Kelly, "The Wright Brothers: A Biography," New York, Dover Publications, 1989; first published by Harcourt, Brace & Company, 1943, "The Wright Brothers: A Biography Authorized by Orville Wright."*
35. *Stanley A. Meyer, U.S. Patent #4,798,661, "Gas Generator Voltage Control Circuit," granted January 17, 1989.*
36. *Stanley A. Meyer, U.S. Patent #4,936,961, "Method for the Production of a Fuel Gas," June 26, 1990.*
37. *Admiral Sir Anthony Griffin, "Water as Fuel," Paper #60 in Proceedings of the Impact of New Technology on the Marine Industries, Maritime Division, Southampton Institute, Warsash, UK, September 13-15, 1993.*
38. *Frank Ogden, "Free Energy Forever?"* Electronics World and Wireless World, *January 1991, pp.10, 12.*