

COLD FUSION: THE HIGH FRONTIER -- IMPLICATIONS FOR SPACE TECHNOLOGY

Eugene F. Mallove
Starbound Engineering
171 Woodhill-Hooksett Rd.
Bow, New Hampshire 03304

Abstract

The confirmation of excess power production and nuclear product evolution in various hydrided metal systems has led many to speculate about technological applications. Here we present a preliminary assessment of how "cold fusion" reactions may affect the technologies that are critical to space exploration. In particular, the implications for space propulsion systems and for non-terrestrial electric power production are considered and found to be potentially very significant. We find that ion-engine thrusters, which are already a well-developed technology, are likely to be the primary beneficiaries of compact cold fusion electric power systems in space. These are highly efficient engines that are characterized by low thrust/weight (T/W), and which are suitable for many deep space missions. It is also possible that high thrust/weight engines that rely on higher-temperature cold fusion reactors could be developed, enabling escape from the surface of celestial bodies, especially Earth. The specific technical parameters of the various engines systems, power modules, and space mission characteristics are compared to define the limits of applicability of cold fusion to space exploration. Though the physical mechanism for "cold fusion" reactions is still being explored by theorists, we refer to this energy source throughout as cold fusion. This is fully justified by common practice -- also because at least some physical systems in which these reactions occur appear to be the cold fusion of deuterons.

Space Exploration: The Turning Point

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

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 on rocket propulsion, yet even within those constraints much has been accomplished. Now

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. 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 fraction 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 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 -- H₂ and O₂ -- 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. 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 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 will 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 thinking of the rocket pioneers about atomic energy for spaceflight (1). 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, Goddard 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."

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

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! 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 (2). In 1989, the present author and colleague Gregory Matloff reviewed the entire field of nuclear propulsion and interstellar flight concepts in a book that is accessible to the wider public (3).

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 Rover and NERVA (Nuclear Energy for Rocket Vehicle Application) programs. 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 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 - 1100 sec, whereas H₂-O₂ 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/sec²) 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. The fundamental rocket equation is:

$$M_0/M_f = \exp(\Delta V/V_e) \quad ,$$

where M₀ is the initial mass of the rocket loaded with propellant; M_f is the "burn out" mass when all propellant has been expended; V_e 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, M₀/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.

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 2,000-7,000 seconds for the gas core nuclear rocket.

None of these fission nuclear rockets are without considerable problems -- including engineering difficulties at elevated temperatures. Each system would release significant radioactivity into the atmosphere were they to be launched from Earth's surface. Even though these systems have high thrust/weight (T/W) ratios and are thus able to lift-off from planetary bodies, their adverse environmental impact would restrict them to operation in space. So these nuclear rockets would have to be boosted into orbit first by chemical rockets. There is another serious disadvantage of fission nuclear rockets: massive shielding of the mission payload and crew against neutron and gamma radiation from the rocket reactor. The reactor itself also has a large mass. Both shielding and reactor add a large weight penalty to the space vehicle, thus detracting to a degree from the advantage of the high Isp.

Cold Fusion for Space

The problems of fission nuclear power for spaceflight would be significantly reduced if there were no radioactive exhaust problem or radiation shielding problem. Therein lies the basic appeal of cold fusion: nearly radiationless nuclear rocketry. A central feature of the scientific controversy surrounding cold fusion -- "If it's nuclear, where's the radiation?" -- turns out to be the prime asset for space. Even if cold fusion reactions could not be engineered 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).

For those who examine the technical literature with a reasonably open mind, the existence of what are now called generically "cold fusion" phenomena -- excess energy production and nuclear reactions near room temperature -- is now beyond dispute. By the spring of 1991 the evidence was, in my view, overwhelmingly compelling (4), now it is 100% certain. The body of scientific evidence for these unexpected, astonishing, and allegedly "impossible" phenomena is now broad, deep, and expanding (5-8). 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*. There exists at the moment no *generally accepted* theoretical framework to understand these phenomena. 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.

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 (9) have demonstrated that a thermal power density of 3-4 kW/cm³ of

cathode material can be created in heavy water electrochemical cells. Kucherov et al (10) have observed similar power densities in metals in low voltage discharge experiments with deuterium gas. Bush and Eagleton (11), using thin films of palladium to coat silver cathodes, have also observed spectacular power densities in the kW/cm³ 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 United States and in the former Soviet Union (12-16). 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 lbs 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.

It turns out that the average power density in these solid core fission reactors approached 3.0 kW/cm³. (There are now reports that Russian nuclear rocket tests have achieved power densities as high as 40 kW/cm³.) 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/cm³ 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.

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. 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 for this has been provided

at this Fourth International Conference on Cold Fusion by Drs. Pons and Fleischmann and by Professor T. Mizuno of Hokkaido University.

Cold Fusion - Ion Engines

Ion engines, which are high Isp and low thrust to weight ($T/W < 10^{-4}$), have always been appealing to space mission planners. Their specific impulse range is 5,000 to 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. When a high T/W rocket fires, it accomplishes the required velocity change within minutes, not months.

Ion engines require a source of electrical power, and it is here that 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. 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, α , the "kilograms per kilowatt" of the system. The SP-100 has a design goal of about $\alpha = 10 \text{ kg/kWe}$ (kWe refers to kilowatts of electricity produced, to distinguish from kW of raw thermal power). Present capability is about $\alpha = 50 \text{ kg/kWe}$. 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 efficiencies, ϵ , 10% and 30%:

Possible Specific Mass of CF Space Electric Power Generation

(Mass of total power system = K * Mass of Pd Electrodes)
 (Assumption: 3.0 kW/cm³ Pd power density)

K	$\epsilon = 0.10$	$\epsilon = 0.30$
	α (kg/kWe)	α (kg/kWe)
10	0.4	0.13
100	4.0	1.3
1000	40.0	13

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 α in the range 1.0 to 4.0 (K = 100) seems realistic -- a factor of 10 or more better than current technology.

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 (17) 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! Space missions are characterized by the ΔV and payload mass required to carry them out. The enormous payload ratios for a single-stage configuration 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 Isp's and T/W's was put on a firm footing by W.E. Moeckel in a classic NASA technical report in 1972 (18). It is worth reproducing several figures from the Moeckel study. By using free-space equations (ignoring lift-off from planets) and several simplifying equations, Moeckel put comparative propulsion system performance on a sound footing. 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 Isp's 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/W's in the 30-60 range, while fission nuclear rockets have engine T/W's 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 ten 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.

Cold Fusion - Space Power Generation

Space stations and other spacecraft require electric power and heating . Compact electric generators based on cold fusion should become standard power equipment for spacecraft. 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 ten person base on Mars (19). 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 m² 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 (20) has discussed the great benefits for Mars missions of extracting rocket propellants from the thin (mostly CO₂) Martian atmosphere. Mars air is taken in, compressed, and the CO₂ separated. A thermal decomposition unit then manufactures bi-propellant rocket fuel, liquid CO and liquid O₂. (Others suggest carrying some liquid hydrogen to Mars and using it to create methane and oxygen rocket bi-propellant from the Martian atmospheric CO₂.) This permits launching a much smaller mass toward Mars on early missions. 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 also 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. 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.

References:

1. William A. Reupke, "The Rocket Pioneers and Atomic Energy," *Journal of the British Interplanetary Society*, Vol.45, No.7, July 1992, pp. 297-304.
2. 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*).
3. E. F. Mallove and Gregory Matloff, *The Starflight Handbook: A Pioneer's Guide to Interstellar Flight*, John Wiley and Sons, New York, August, 1989.
4. E. F. Mallove, *Fire from Ice: Searching for the Truth Behind the Cold Fusion Furor*, John Wiley & Sons, 1991.
5. 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.
6. 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).
7. Hideo Ikegami (editor), *Frontiers of Cold Fusion, Proceedings of the Third*

- International Conference on Cold Fusion (Nagoya, Japan 21-25 October, 1992)*, National Institute for Fusion Science, Nagoya 464-01, Japan (698 pages).
8. Peter L. Hagelstein, "Summary of the Third International Conference on Cold Fusion in Nagoya," MIT Research Laboratory for Electronics report, January, 1993 .
 9. Martin Fleischmann and Stanley Pons, "Calorimetry of the Pd-D₂O system: from simplicity via complications to simplicity," *Physics Letters A*, Vol.176, May 3, 1993, pp.118-129.
 10. 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.
 11. 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.
 12. 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.
 13. 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.
 14. Milton Klein, "Nuclear Rocket Propulsion - The Past Is Prelude," *Fusion Technology*, Vol.20, Dec., 1991, pp.693-697.
 15. R.J. Bohl, F.P. Durham, and W.L. Kirk, "Nuclear Rocketry Review," *Fusion Technology*, Vol.20, Dec.1991, pp.698-709.
 16. O.C. Jones, "Rotating Fluidized Bed Reactor for Space Power and Propulsion: A Status Report," *Fusion Technology*, Vol.20, Dec. 1991, pp.741-746.
 17. 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.
 18. W.E. Moeckel, "Comparison of Advanced Propulsion Concepts for Deep Space Exploration," NASA Technical Note TN D-6969, Lewis Research Center, September, 1972.
 19. David H. Atkinson and Owen Gwynne, "Design Considerations for a Mars Solar Energy System," *Journal of the British Interplanetary Society*, Vol.45, No.5,, May, 1992, pp.183 -194.
 20. J.R. French, "Some Unconventional Approaches to the Exploration of Mars," *Spaceflight*, Vol.33, February, 1991, pp.62-66.

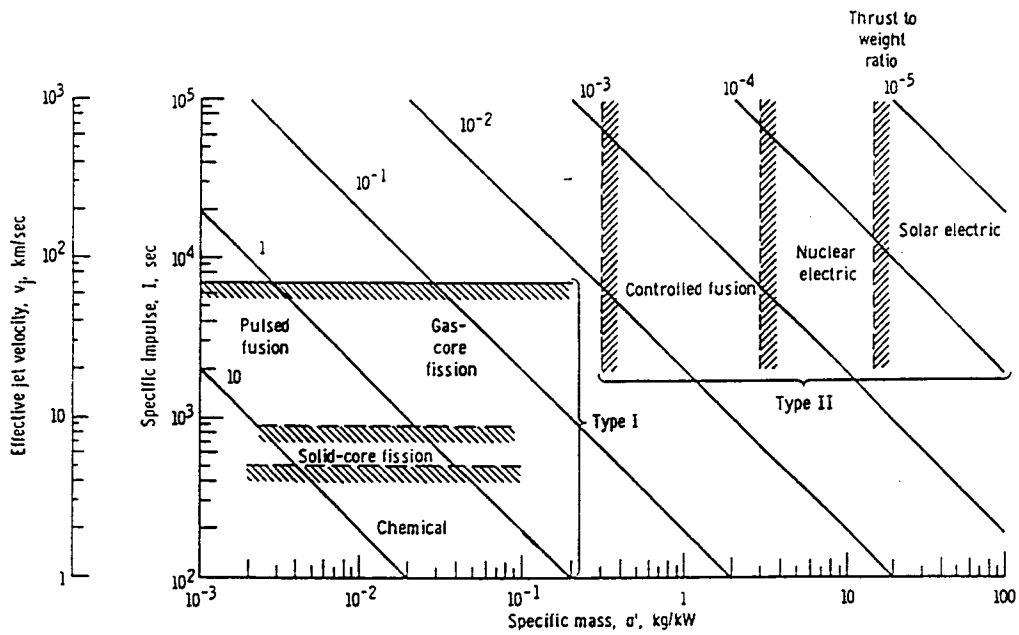


Figure 1. Rocket Propulsion Performance Parameters

From: W.E. Moeckel, "Comparison of Advanced Propulsion Concepts for Deep Space Exploration," NASA TN D-6968, September, 1972.

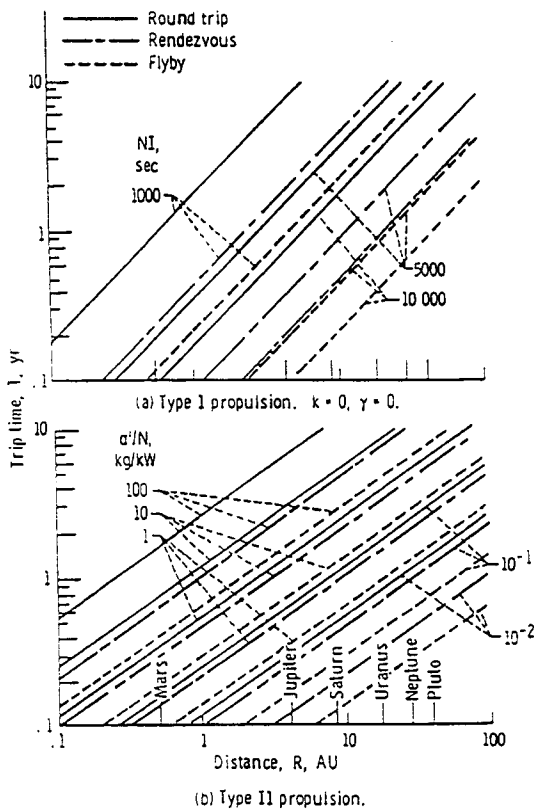


Figure 2. Interplanetary Distance Versus Trip Time

From: W.E. Moeckel, "Comparison of Advanced Propulsion Concepts for Deep Space Exploration," NASA TN D-6968, September, 1972.

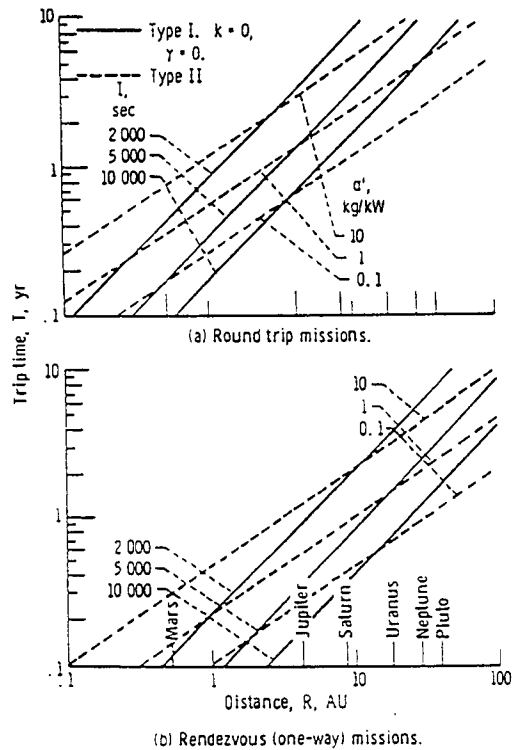


Figure 3. Comparison of Type I and Type II Propulsion for Planetary Distances. $N = 1$.

From: W.E. Moeckel, "Comparison of Advanced Propulsion Concepts for Deep Space Exploration," NASA TN D-6968, September, 1972.