Powered flight to Mars in less than two days

Heinz Horeis, editor of the German Fusion *magazine, presents some promising calculations for the fusion propulsion systems projected to be available in the desired time-frame.*

This working paper by Heinz Horeis gives parameters for developing fusion powered space propulsion systems. As we have reported, work is now ongoing on first-generation fusion propulsion systems. For example, one design now being worked on would use helium fuel and a tandem mirror machine, to achieve an acceleration of .01 G. We will be reporting on these developments on an ongoing basis.

Practically, the problem which we face in developing a fusion propulsion system, is the relative stagnation imposed upon fusion research by persistent underfunding. This working paper by Horeis is important because it breaks through the imposed pessimism of working within the "realities" of budgetary constraints, and poses the reality that we must rapidly develop fusion power, not only for its industrial potential on Earth—but because its development is key to successful colonization of space.

Last year, two proposals for a Moon/Mars project were published, one by the National Commission on Space,[1] the other by Lyndon LaRouche.[2] Both proposals suggest the same schedule—returning to the Moon around the turn of the century, the beginning of the colonization of Mars 40 years from now—and both agree, that the work on this project has to begin right now if the first settlers are to go to Mars in four decades. The main difference between the two proposals, however, is that the National Commission on Space primarily sticks to available technology or extensions of available technology, while LaRouche's proposal concentrates on projected new technologies as the basis for the project.

This especially applies to the question of propulsion. How is Mars to be reached? By means of available chemical rockets, by low thrust-systems like electric propulsion, which exist as experimental devices, or by some new advanced propulsion systems like the fusion drive, as proposed by LaRouche, which still have to be developed?

Going to Mars with available technology (e.g., chemical rockets) will take months or years, as Wernher von Braun already outlined 30 years ago.[3] After a short boost period, the rocket drifts on a minimum-energy path toward its goal—carrying very little payload and providing living conditions that put a very large amount of stress on the people on board. In particular, the long period of zero-gravity during the drift period will most probably have bad effects on the health of the crew.

In this manner, some first exploration missions to Mars could be flown, comparable to Columbus's trip to America almost 500 years ago. The colonization of Mars and eventually the Solar System, however, will not be possible under these conditions. Turning Mars into a human colony would mean that millions of tons of freight, instead of some tens or hundreds of tons, and 100,000 people will be sent traveling through space.

For this task, technologies are needed that allow for continuously powered flights with a large payload, reducing traveling time drastically, to days instead of months, and creating an "artificial gravity" on board, which would provide better living conditions and prevent health hazards.

To continuously power a rocket, however, fuels with a very high energy density are needed. There are only two candidates for this: antimatter and fusion power, of which the latter could be realized in the indicated time frame. At least on paper, the scientific feasibility of a fusion drive has been established by Dr. Fred Winterberg,[4] and by a working group of the British Interplanetary Society, which has designed "Project Daedalus," a fusion-powered starship.[5] Other work is being conducted by scientists at the Lawrence Livermore Laboratory in California, and at the University of Wisconsin.

What follows are some elementary calculations of the physical-technical dimensions of a flight to Mars using fusion-powered spaceships. These are very simple and very rough estimations, and should only be seen as indicative of orders of magnitude. More detailed studies should follow, and it is hoped, that this working paper may trigger the necessary work.

I. Fusion reactions and their energy density

First, some basic facts on fusion power. The reactions listed below could be used for commercial fusion:

1) $^2D + {}^3T \rightarrow {}^4He\ (3.5) + {}^1n\ (14.1),\ \alpha = 0.0038$

2) $^2D + {}^2D \rightarrow {}^3T\ (1.01) + {}^1n\ (3.02),\ \alpha = 0.0011$

3) $^2D + {}^2D \rightarrow {}^3He\ (0.82) + {}^1n\ (2.45),\ \alpha = 0.0009$

4) $^2D + {}^3He \rightarrow {}^4He\ (6.6) + {}^1p\ (14.7),\ \alpha = 0.0039$

α gives the fraction of the mass that is converted into energy; the values in parentheses indicate the energy of the reaction products in million electron volts.

Out of these four reactions, only the last, the reaction D-Helium-3, is a candidate for a fusion drive. It has the highest α value, and the energy is bound almost completely to charged particles and therefore can be controlled and directed with magnetic fields. There will also be the neutron producing D-D reaction, but its share is relatively small with 1.5 to 5 percent.

The following gives the energy density of some fusion fuels, compared to some other energy sources that are or could be used for rocket propulsion. The values refer to 1 kilogram of mass:

Chemical (H_2/O_2)	3.72 kWh	1.34×10^7 Joules
Fission	18×10^6 kWh	6.5×10^{13} J
Fusion (D-D)	25×10^6 kWh	9.0×10^{13} J
Fusion (D-T)	92.5×10^6 kWh	3.3×10^{14} J
Fusion (D-^{3}He)	97.5×10^6 kWh	3.7×10^{14} J

Of crucial importance for a rocket engine is the exhaust velocity w, that is the velocity of the respective reaction products. They compare as following:

Chemical	
Alcohol/O ("Aggregat-4")	$w = 2{,}000$ m/sec
H_2/O_2	$w = 4{,}500$ m/sec
Fission	
Nuclear-electric	$w = 30{,}000 - 50{,}000$ m/sec
Fusion	$w = 10^7$ m/sec

The proton, produced by the D-^{3}He reaction, has a velocity $v = 5.5 \times 10^7$ m/s and the helium nucleus $v = 2 \times 10^7$ m/s. In Project Daedulus, a burn-up fraction of 15% of the pellet mass is assumed, so that for the whole pellet mass, an average velocity of $v = 10^7$ m/sec is achieved.

II. Rocket equations

The basics have been known since Hermann Oberth and Konstantine Tsiolkovsky performed this work, in the first decades of this century. The mass m of a rocket receives an acceleration a through the thrust, S. If we have:

r = mass flow rate in the engine, in kilograms/second,
w = exhaust velocity (m/sec),
m_o = lift-off mass (kg), m_E = final mass (kg),
m_T = fuel mass (kg).

With thrust $S = rw$, it follows

$rw = ma = m \dfrac{dv}{dt}$. With $m(t) = m_o - rt$ we have

$$\frac{dv}{dt} = -\frac{rw}{m_o - rt} \text{ giving}$$

$$v = -\int_o^t \frac{rw}{m_o - rt} dt$$

Integration gives

$$v = w \ln \frac{m}{m_o - rt} \quad (1)$$

In case that all the fuel is burned up during acceleration, then $rt = m_T$, and
with $m_o = m_T + m_E$ the end velocity is

$$v_e = w \ln m_o/m_E \quad (2)$$

m_o/m_E indicates the mass ratio R.

$$R = e^{v/w} \quad (3)$$

For the mass flow, we will have

$$r = (m_o/t)\,(1 - e^{-v/w}) \text{ or } r = (m_o/t)\,(1 - e^{at/w}) \quad (4)$$

III. Fusion powered flight to Mars

To estimate the time frame, we will calculate flights to Mars for minimal and maximal values of distances Earth to Mars and the acceleration.

Distance Earth/Mars:
mimimal: 60,000,000 km
maximal: 400,000,000 km
Acceleration:
minimal: 1/6 g (lunar gravity)
maximal: 1 g (Earth gravity)

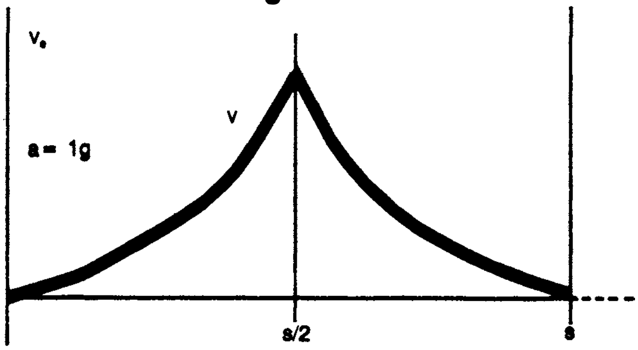
Of course, other accelerations could be thought of, but these values should, concerning their effects on human beings, be appropriate limit values.

For the calculations given here, effects such as solar gravity are (and can be) neglected. We assume that the Mars ship accelerates for half the distance, s, with constant acceleration $a = 1$ g, or $a = 1/6$ g, and then decelerates with 1 g, or 1/6 g for the remaining half.

Figure 1 is an a/v-distance diagram.

FIGURE 1

An a/v-distance diagram



Velocity, time of flight, and mass ratios

With $v = (2as)^{1/2}$ and $t = (2s/a)^{1/2}$, we get for the respective half distances the values for v_e and t shown in **Table 1.** Note the short flight times: less then 2 days for the shortest distance and 11 days for the longest, compared to 260 days for chemical rockets.

Table 1

Calculation of velocity and time of flight

$v = (2as)^{1/2}$

$t = (2s/a)^{1/2}$

Distance	At acceleration 1 g	Time
30×10^9 m	$v_e = 7.7 \times 10^5$ m/sec	$t_e = 77{,}460$ sec (21 h)
200×10^9 m	$v_e = 2 \times 10^6$ m/sec	$t_e = 200{,}000$ sec (55 h)
	acceleration 1/6 g	
30×10^9 m	$v_e = 3.16 \times 10^5$ m/sec	$t_e = 189{,}700$ sec (53 h)
200×10^9 m	$v_e = 8.16 \times 10^5$ m/sec	$t_e = 489{,}900$ sec (136 h)

According to $R = e^{v/w}$, the mass ratio for the different values of v are determined. Covering the total distance to Mars would simply require doubling the velocities we attained above (**Table 2**).

This assumes that fuel for the travel back would be available in Mars orbit. If fuel for both ways has to be stored on board, then we have to calculate with four times the velocity values. In Table 2, the respective R-values are given in parentheses.

Table 2

Calculation of mass ratio R

$w = 10^7$ m/sec.

Distance	a=1 g	a=1/6g
60×10^9 m	R = 1.17 (1.36)	R = 1.07 (1.13)
400×10^9 m	R = 1.49 (2.23)	R = 1.18 (1.39)

As can be expected from the high exhaust velocity of a fusion drive, the values shown in Table 2 are extremely good values for R, dwarfing by far everything we know from chemical propulsion. We illustrate these values in **Table 3,** where they are converted to some actual mass figures. As an example, we take a small spaceship with the lift-off mass, $m_o = 100$ t; m_T is the mass of the fuel and m_E the final mass, including payload and the mass of the ship itself.

Table 3

Mass values for a spaceship of 100 tons lift-off mass

	m_o	m_E	m_T
R = 1.07	100 t	94.5 t	6.5 t
R = 1.17	100 t	85.5 t	14.5 t
R = 1.18	100 t	84.7 t	15.3 t
R = 1.49	100 t	67.2 t	32.8 t
R = 2.23	100 t	45.0 t	55.0 t

For illustration and comparison, in **Table 4,** the R-values for chemical and fission propulsion are calculated, based on the same acceleration values as above.

Table 4

Chemical and fission propulsion R-values

Distance Earth/Mars	System	a=1g	a=1/6g
60,000,000 km	Chemical	$R > 10^{99}$	$R = 10^{61}$
	Fission	$R = 5 \times 10^{16}$	$R = 7.4 \times 10^6$
400,000,000 km	Chemical	$R > 10^{99}$	$R = 6.3 \times 10^{78}$
	Fission	$R = 2.7 \times 10^{43}$	$R = 7.3 \times 10^8$

As one can see, continously powered planetary flights, with accelerations that are appropriate for human beings, are totally impossible with chemical or nuclear-electric propulsion. The total mass in the universe would not be enough to fly a chemical rocket with 1 g or 1/6 g to Mars!

Mass flow and power of a fusion drive

These values for flight-time and R are extremely promising and exciting. However, to this point, they are just paper values derived from simple equations, which (except for w) do not take into account parameters that would express the physical-technical properties of a fusion drive. To obtain a first, rough approximation as to the feasibility of a fusion drive with a performance as described by the values above, we must look at the mass flow and the power of such an engine.

One can estimate the average mass flows of a fusion engine (**Table 5**) using equation (4). This is calculated for 1

Table 5
Mass flows of fusion engine

Time	a=1 g	a=1/6 g
t = 10 sec	r = 100 g/sec	—
t = 77,460 sec	r = 96 g/sec	—
t = 10 sec	—	r = 16.6 g/sec
t = 489,900 sec	—	r = 16.0 g/sec

Table 6
Fusion engine with mass flows of 500 g/sec

	m_o	m_T	m_E	
1g				
R = 1.17	500 t	70 t	430 t	Mars-Min
R = 1.49	500 t	165 t	335 t	Mars-Max
R = 2.91	500 t	330 t	170 t	Saturn
1/6 g				
R = 1.07	3,000 t	200 t	2,800 t	Mars-Min
R = 1.18	3,000 t	500 t	2,500 t	Mars-Max
R = 1.55	3,000 t	1,100 t	1,900 t	Saturn

g or 1/6 g at the beginning ($t = 10$ sec) and at the end of the flight ($t = t_e$), again for a small ship with $m_o = 100$ tons.

Because of the low R values (i.e., small share of fuel mass), the mass flow through the engine per second decreases only slightly in the course of the flight. It is almost constant, so that we can assume average values: 0.1 kg/sec for 1 g and 0.016 kg/sec for 1/6 g.

How would these values fit for a fusion drive, based on inertial confinement?

In inertial confinement fusion, pellets with a mass of a few grams are ignited with a frequency, f, of several 10 to a few 100 Hertz. In *Project Daedalus*, the following values are assumed for the fusion engine:

Pellet mass $m = 2.85$ g; frequency $f = 250$ Hz

This gives a mass flow $r = mf = 710$ g/sec. Following this, we may assume that a mass flow of several 100 g/sec may be mastered in the future.

The energy released is enormous. Such a pellet would release an energy $E = 10^{12}$ J = 1 terrajoule (TJ). With a frequency of 100 Hz, such a fusion engine would have a power of 100 TW! This is 10 times the power produced and consumed today by man on Earth. With interplanetary flight, we therefore move into the "terra era," where man will work with terrawatts in the same natural way as he does today on Earth with kilowatts.

The mass of the engine

Let us assume in the following that a fusion engine will work with a mass g/sec.

With 1 g, the maximum mass that could be accelerated would be roughly $m_o = 500$ t. The critical element would be the mass of the engine, as **Table 6** shows. Here the masses for $R = 1.17$ (distance Earth/Mars = 60,000,000 km) and $R = 1.49$ (400,000,000) are calculated. One sees that if the engine does not weigh more than 200 t, then we can have payloads of more than 200 and 100 t, respectively, which would be acceptable. For flights farther into the Solar System, however, the mass of the

A flight to Saturn (average distance 1.43×10^{12} m) with 1 g would give $R = 2.91$ and a final mass $m_E < 200$ t. Accelerating with 1/6 g and again $r = 500$ g/sec would give a lift-off mass of several thousand tons. The mass of the engine would be around 10% of the final mass.

Therefore, one may conceive of a flotilla of small Mars ships (500 tons and more), primarily for transporting people at 1/6 g to 1 g, and larger ships that fly large freight masses with small accelerations.

For illustrative purposes, the division "fast transport of persons/slow freight transport" can be quantified, based on conditions here on Earth, by taking the ratio of fast airplane to slow ship transport. Here, the time ratio is somewhere around 1:20 to 1:30. So, if the fast flight to Mars at 1 g would last 75 hours on average, this would give us 1,875 hours (80 days) for slow freight transport and (average distance Earth/Mars of 230 million km) an acceleration $a = 0.02$ m/sec = 2/1,000 g. Then we would have

$R = 1.014$, and, for $m_o = 100$ t, $r = 0.2$ g/sec

Again assuming an engine with $r = 500$ g/sec, we could power a spaceship with $m_o = 250{,}000$ t obtaining the following shares:

$R = 1.014$
$m_o = 250{,}000$ t
$m_T = 3{,}500$ t
$m_E = 246{,}500$ t

To conclude: These rough estimations indicate, that fusion for spaceship propulsion bears huge promise for future space flight. It will be the key to opening up the Solar System for human settlement and exploitation, just as railways opened up the American continent. If man wants to be on Mars in 40 years, then it is about time to start real work on this project.

Notes

1. National Commission on Space, *Pioneering the Space Frontier*, New York, 1986.
2. Lyndon H. LaRouche, Jr., "The Crowning Achievement of the Reagan Administration: The Moon-Mars Colonization Mission," background paper circulated at the European Conference of the International Caucus of Labor Committees, Wiesbaden, West Germany, June 1986.
3. Wernher von Braun, *The Mars Project*, 1948.
4. Friedwardt Winterberg, *Rocket propulsion by thermonuclear microbombs ignited with intense relativistic electron beams*, *Raumfahrtforschung*, 15, 208-217 (1971).
5. British Interplanetary Society, *Project Daedalus*, London, 1978.