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NUCLEAR THERMAL ROCKETS USING INDIGENOUS EXTRATERRESTRIAL PROPELLANTS

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ABSTRACT

This paper presents a preliminary examination of a novel concept for a Mars and outer solar system exploratory vehicle. Propulsion is provided by utilizing a nuclear thermal reactor to heat a propellant volatile indigenous to the destination world to form a high thrust rocket exhaust. Candidate propellants whose performance, materials compatibility, and ease of acquisition are examined include carbon dioxide, water, methane, nitrogen, carbon monoxide, and argon. Ballistic and winged supersonic configurations are discussed. It is shown that the use of this method of propulsion potentially offers high payoff to a manned Mars mission, both by sharply reducing the initial mission mass required in low Earth orbit, and by providing Mars explorers with greatly enhanced mobility in traveling about the planet through the use of a vehicle that can refuel itself each time it lands. Utilizing the nuclear landing craft in combination with a hydrogen fueled nuclear thermal interplanetary vehicle and a heavy lift booster, it is possible to achieve a manned Mars mission in one launch. Utilizing such a system in the outer solar system, it is found that a low level aerial reconnaissance of Titan combined with a multiple sample return from nearly every satellite of Saturn can be accomplished in a single launch of a Titan IV or STS. Similarly a multiple sample return from Callisto, Ganymede, and Europa can also be accomplished in one launch of a Titan IV or STS.

INTRODUCTION

Interplanetary travel and colonization can be greatly facilitated if indigenous propellants can be used in place of those transported from Earth. Nuclear thermal rockets, which use a solid core fission reactor to heat a gaseous propellant, offer significant promise in this regard, since, in principle, any gas at all can be made to perform to some extent. In this paper we present a preliminary examination of the potential implementation of such a concept in the context of manned Mars missions. The vehicle in question we hereby christen the NIMF, for Nuclear rocket using Indigenous Martian Fuel.

CANDIDATE MARTIAN PROPELLANTS

The atmosphere of Mars consists of 95.0% carbon dioxide, 2.7% nitrogen, and 1.6% argon, all of which are candidate fuels for a NIMF. Water could also be used after harvesting ice or permafrost. Carbon monoxide could be manufactured by stripping CO_2, and could either be used as a propellant directly, or reacted with water to produce methane propellant.The following chart shows the ideal specific impulse obtainable with each of the above propellants at various temperatures.

Table 1

Ideal Specific Impulse of Martian Propellants

Temperature	CO_2	Water	Methane	CO or N_2	Argon
2800 K	283	370	606	253	165
3000 K	310	393	625	264	172
3200 K	337	418	644	274	178
3500 K	381	458	671	289	187

In the table above, 2800 K may be regarded as a safe operating temperature, as NERVA carbide (Koenig, 1986)[3], uranium-thorium oxide, and cermet (Cowan, et al., 1988)[1] fuel elements have been extensively and successfully tested in this range. Some of the final NERVA tests and cermet data both indicate that 3200 K may eventually be attainable. The final temperature of 3500 K can be taken as a ultimate upper limit to what a solid core nuclear rocket may be expected to achieve.

We now examine the characteristics of each of the candidate propellants.

Carbon Dioxide

Carbon Dioxide is the most readily accessible of all the candidate martian propellants. Composing 95% of the atmosphere, it can be obtained by pumping the martian air into a tank. At a typical martian temperature of 233 K, carbon dioxide liquifies under a pressure of 10 bars. Under these conditions, assuming an isothermal compression process, liquid CO_2 can be manufactured for an energy cost of just 84 kW-hrs per metric ton. The NIMF engine produces over a thousand MW (thermal). If an electrical capacity of 1 MWe is built in as well, then the (2800 K, 40 MT) NIMF would be able to fuel itself for a flight into a high orbit in less than 14 hours! Liquid CO_2 has a density 1.16 times that of water and is eminently storable under martian conditions.

A 40 MT CO_2 propelled NIMF vehicle with a specific impulse of 280 seconds would require a mass ratio of 3.8 to ascend to Low Mars Orbit, or 8.3 to fly directly from the Mars surface into a Hohmann Transfer orbit to Earth, both of which are attainable due to the high mass density of liquid CO_2. Reactor power levels of about 1100 MWth would be required to generate sufficient thrust for the ascent to orbit, while 2400 MWth would be required for the direct Trans-Earth Injection mission.

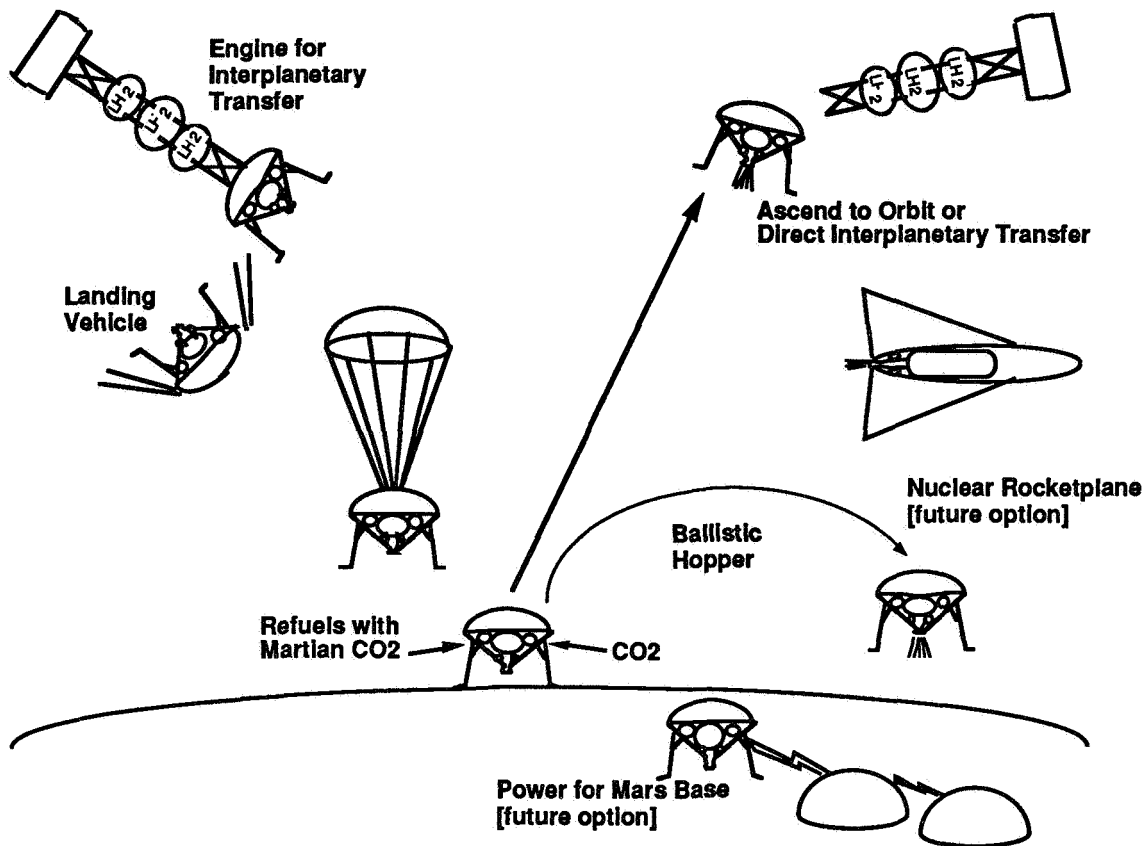A CO_2 NIMF operating in a variety of modes is depicted in fig. 1.

Figure 1 The NIMF (Nuclear rocket using Indigenous Martin Propellants)

Since CO_2 is so readily acquired, it is quite convenient for use for multiple suborbital hops, allowing a Mars exploration mission to visit many sites. The vehicle for such an application (which would also function as the surface to orbit ascent vehicle) could take the form of either a ballistic hopper or a supersonic (Mach 4-5) winged aircraft. Such an aircraft could function either as a pure rocketplane, or use airborne jet intake of CO_2 to extend its range. Because of the high speeds and power levels available from NIMF propulsion, wing sizes could be quite modest, similar to those on the Space Shuttle orbiter. Landing and takeoff would require VTOL ability, and be accomplished either in the manner of the Harrier or the X-13.

At high temperatures, both carbon dioxide and water become oxidizers, making it unlikely that a CO_2 or water NIMF could utilize the same carbide fuel elements developed for the NERVA hydrogen propelled nuclear engine program. Instead, oxide fuel elements would have to be used. Fuel pellets composed of a combination of uranium-thorium oxide have been made with melting points above 3300 K. If coated with another oxide to prevent fission product migration into the propellant exhaust, such pellets should be able to sustain CO_2 or water driven NIMF engines with propellant temperatures of about 3000 K. The disadvantage of such oxide fuel pellets is that they would probably not be compatible with hydrogen propellant, in which case a high Isp interplanetary transfer vehicle would have to employ a separate NERVA type engine.

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Water

While involving greater uncertainty and complexity in its acquisition, the use of water propellant allows for remarkable performance. For example, a 3000 K water propelled NIMF taking off from the martian surface for Low Earth Orbit would have a mass ratio of 5.4 and require about 2000 MWth for liftoff. If a base on Phobos is used as a point of departure, a water propelled NIMF would be able to fly to Earth, aerobrake into a loosely bound orbit, and return to Mars without refueling.

The main problem with the use of water is finding it, and the second is harvesting it. It is believed by many planetary scientists that vast quantities of water may exist on Mars in the form of permafrost covered over by a few feet of sand. After all, the planet once had flowing rivers. The existence of such quantities of water on Mars may be verified by the unmanned probes planned by the U.S. and the Soviets for the 1990s. At the present, the only large sources of water known for certain to exist on Mars is in the north polar cap, which however is a very inconvenient place from which to launch into an orbit useful for Earth return, as the required inclination change is large. If permafrost is discovered, water will become more generally available, but it will require an operation of some complexity to harvest it. It is therefore difficult to see how an initial manned mission could be planned based on the assumption of securing water fuel for the return trip. However, once a martian base is established, locally mined water could function as a near ideal fuel for both Earth return, near Mars, and beyond Mars operations.

Methane

If water is acquired on Mars, then methane can be produced (along with oxygen) by using heat from the nuclear reactor to strip CO from martian CO_2, and then reacting the CO with H_2O in the water gas shift reaction to produce hydrogen and CO_2. Some of the CO_2 is recycled to be stripped, and the remainder is then catalytically reacted with the hydrogen to produce methane and water. As can be seen from Table 1., methane is an excellent candidate propellant for a NIMF vehicle, yielding specific impulses well in excess of 600 seconds. Furthermore, since it does not contain oxygen, the use of methane eliminates one of the major problems associated with either CO_2 or H_2O, namely oxygen attack, and would be compatible with conventional NERVA carbide fuel elements. Methane, however, fully dissociates at temperatures of interest for nuclear propulsion, and the free carbons thus created may cause coking problems. This is a question that must be resolved experimentally.

Liquid methane would have to kept refrigerated on Mars, but this is not expected to present significant difficulties. Methane liquifies at 135 or 166 K, at 5 or 20 atmospheres pressure, respectively.

Other NIMF Propellants

Nitrogen, carbon monoxide, and argon are also potential NIMF propellants. However, as can be seen from table 1., their performance is inferior to that of the much more accessible CO_2. Compared to the 84 kWe/MT cost of liquifying CO_2, these propellants require about 5 to 10 MWe/MT to produce (Meyer and McKay, 1984)[5]. In addition, these three propellants are all moderately cryogenic, requiring storage temperatures in the 100 K range. The primary advantage of these fuels over CO_2 is their lack of chemical reactivity with fuel or cladding materials that are also compatible with hydrogen. Thus the same reactor which uses carbon monoxide for propellant for ascent to orbit could also use hydrogen propellant, taking advantage of its 950 second Isp for interplanetary orbital transfers.

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Finally it should be noted that if water is available, it is possible to combine hydrogen from the water with nitrogen to form ammonia, a non cryogenic, oxygen free propellant capable of yielding an Isp of around 450 seconds at reactor temperatures of 3000 K. The processes involved may be excessively complex and energy expensive, however.

NIMF CONFIGURATIONS

Artist's conceptions of two alternative NIMF configurations are depicted in figs. 2 and 3. The first, (fig. 2)by Martin Marietta artist Robert Murray, shows a NIMF ballistic vehicle standing on the martian surface. The nuclear engine is at the bottom, and is surrounded by a coaxial fuel tank, which when filled, augments the solid lithium/tungsten shadow shield with a several meter thick four-pi shield of liquid CO_2. This liquid coaxial shield facilitates human operation on the surface in the immediate vicinity of the NIMF by protecting against gamma rays released by fission decay products. Positioned above the shadow shield is the main spherical fuel tank, above which is the machine deck incorporating the CO_2 intake pumps. Above this are the habitation and command decks, and at the very top is a storage dome. Thus, when the main engine is firing the crew is protected from radiation by the shadow shield, the massive amount of liquid CO_2 in the main tank, by the structures in the machine deck and the lower habitation deck, and by distance. The NIMF's fuselage acts as an aerobrake, with a L/D approaching unity.
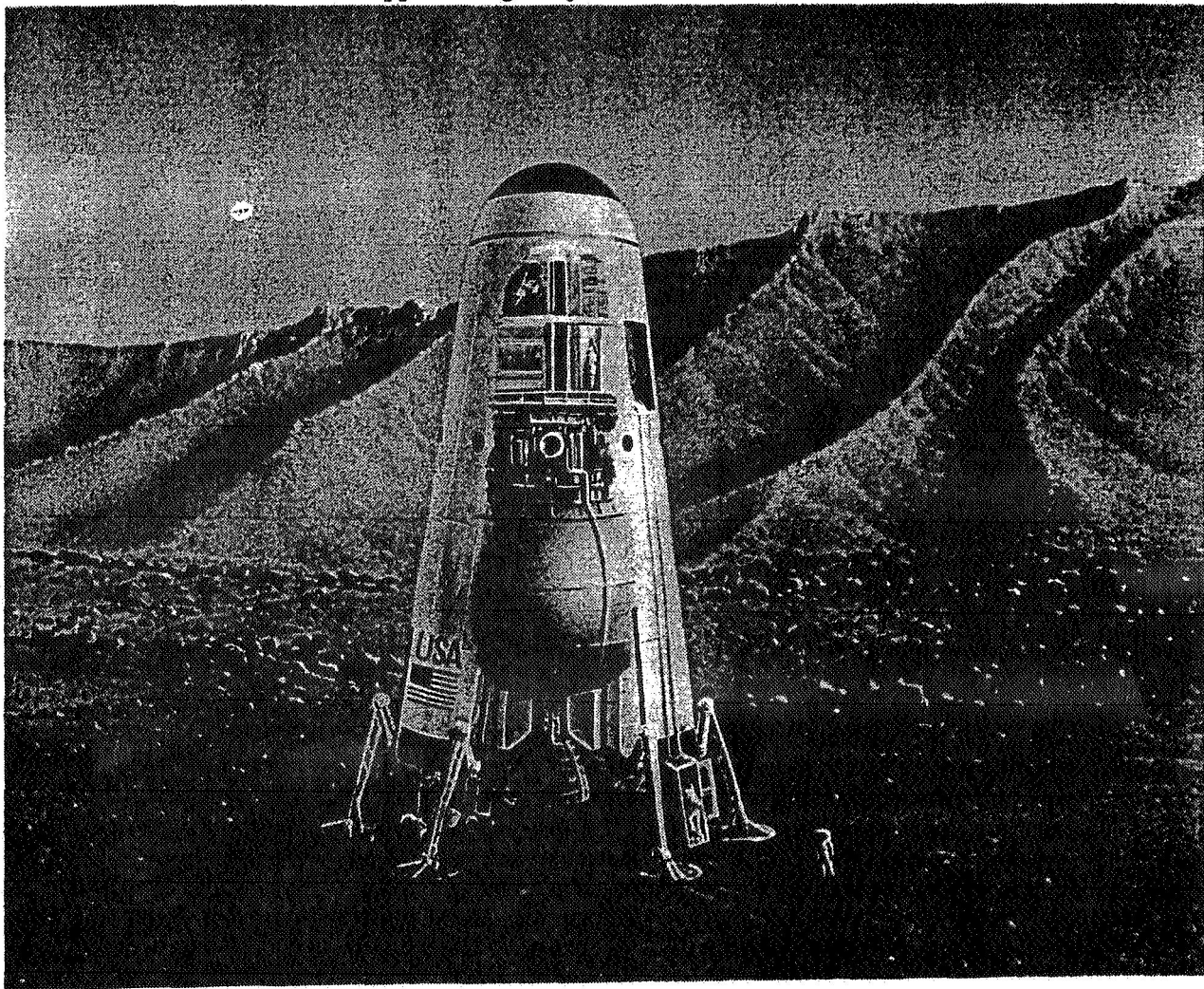

Figure 2 NIMF Ballistic Ascent/Descent Vehicle on the Martian Surface

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The second drawing (fig. 3), also by Murray with the assistance of free lance artist Jeff Danelek, depicts a winged NIMF rocketplane on the surface of Mars. Once again, the reactor shadow shield is supplemented by a coaxial four-pi liquid shield, by the main fuel tank forward of the reactor, and by a machine compartment. Because the craft flies at supersonic speeds (long range level flight at Mach 4), the wings are fairly modest deltas, very unlike the delicate albatross like ultra-high L/D wings proposed for martian aircraft in the past. The winged NIMF's L/D is equal to 4, and the craft, which has orbital capability, functions as its own aerobrake, much in the manner of the Space Shuttle Orbiter. Landing is accomplished by increasing the angle of attack to maintain lift as the glide decelerates, until a speed of about Mach 1 is attained. At this point, the craft flares up and fires its 4 VTOL rockets positioned on its underside to eliminate its remaining forward velocity and accomplish a Harrier like landing. The VTOL rockets generate thrust by releasing hot CO_2 gas which is piped to them from the reactor outlet. Cargo, land rovers, and crew can conveniently exit onto the martian surface by means of the landing ramp which lowers from the forward stowage area, just below the control deck and forward of the habitation compartments.
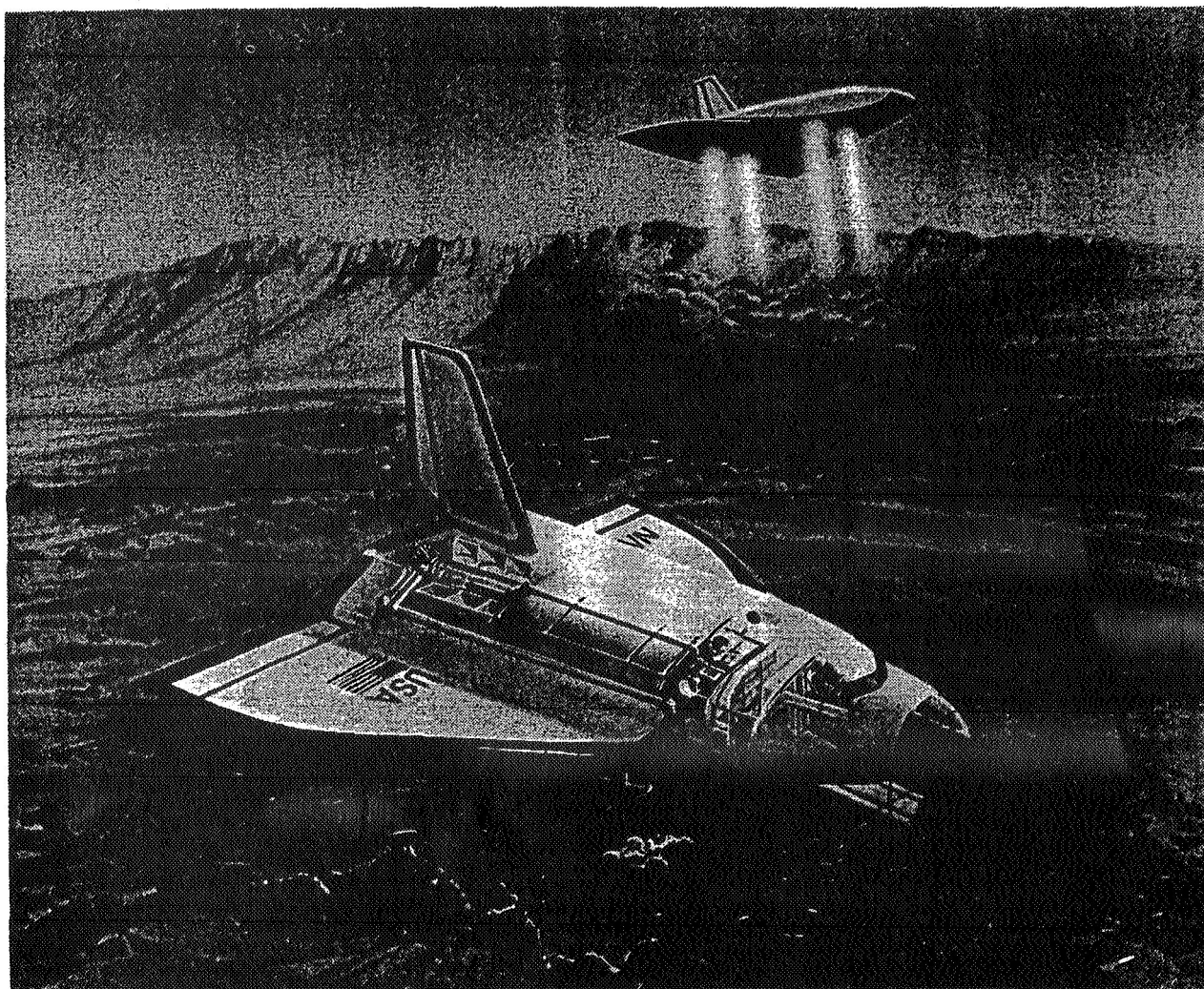

Figure 3 NIMF rocketplane. Aerodynamic flight at Mach 4 allows modest wing area. Takeoff and landing is accomplished using 4 ventral VTOL thrusters.

A MANNED MARS MISSION IN A SINGLE LAUNCH

Since the days of the Apollo program, NASA's thinking about manned planetary landings has been dominated by approaches based on a combination of an orbiting mothership containing long term living quarters and a small landing craft, a fraction of which manages to ascend to orbit after a stay on the surface. The reason for such an approach has always been the fact that any mass lowered into a planet's gravity well that requires return to space will require additional fuel mass to accomplish such an ascent. Furthermore, since this fuel mass itself must be transported from Earth, which requires still more fuel, ultimately the entire mass and cost of the mission is multiplied. With the advent of the NIMF, however, such logic is no longer valid. In fact, since any mass landed upon Mars can be lifted back to orbit using readily available indigenous propellant, it becomes advantageous to abandon the concept of the orbiting mothership altogether, and instead land the entire spacecraft living quarters on the planet's surface. In other words, the NIMF and the interplanetary vessel are one and the same. All that is left in orbit is an automated vehicle consisting of either a cryogenic or nuclear thermal orbital transfer propulsion unit with associated fuel and tankage.

The use of the NIMF in this, its proper mission architecture was examined in three alternative scenarios. In each of these scenarios, a 40 metric ton NIMF carrying a three person crew was projected out of a 300 km LEO orbit onto a minimum energy trajectory towards Mars. The NIMF lands on Mars, and hops around visiting various sites, ultimately returning to Earth via a Hohmann transfer orbit. The three scenarios examined are given below.

Scenario 1: An expendable orbital transfer vehicle (OTV) propels the NIMF out of LEO onto a minimum energy transfer orbit to Mars. Upon reaching Mars, the NIMF aerobrakes and lands. The NIMF then explores Mars, hopping around to visit many sites. Finally the NIMF takes off Mars, propelling itself directly into a minimum energy orbit to Earth. Upon reaching Earth, the NIMF aerobrakes into LEO.

Scenario 2: An OTV propels the NIMF out of LEO onto a minimum energy transfer orbit to Mars. Upon reaching Mars, the NIMF and the OTV aerobrake separately, leaving the (automated) OTV in Low Mars Orbit (LMO), while the NIMF lands. After exploring Mars, the NIMF takes off for LMO and rendezvous with the OTV. The OTV then drives itself and the NIMF out of LMO onto a minimum energy orbit towards Earth. Upon reaching Earth, the NIMF and the OTV aerobrake into LEO.

Scenario 3: An OTV drives the NIMF onto a minimum energy transfer orbit to Mars. Upon reaching Mars, the OTV rocket brakes itself 1 km/s into Mars' gravity well, while the NIMF aerobrakes and lands. After exploring Mars, the NIMF ascends to orbit and rendezvous with the OTV. The OTV then drives both onto a minimum energy orbit towards Earth. Upon arrival, the OTV rocket brakes both into LEO.

Scenario 1 would require interplanetary transfer to take place under zero-gravity conditions. In scenarios 2 and 3, various amounts of artificial gravity could be provided by linking the NIMF and the OTV with a tether, separating the two at a distance, and spinning up the assembly.

Three different OTV propulsion systems were considered. The first was a cryogenic LOX/hydrogen engine with a specific impulse of 470 seconds. The second was a NERVA type nuclear thermal engine with an Isp of 950 seconds. The third was a radial flow nuclear thermal rocket (RFNTR) such as that invented by Carl Leyse and his collaborators at the Idaho National Engineering Laboratory, which uses lower chamber pressures and higher

temperatures than a conventional NERVA engine to achieve partial hydrogen dissociation and an Isp of 1300 seconds (Leyse, 1988)[4]. The cryogenic propulsion OTV was assumed to consist of several stages, one for each required burn, with each stage having a mass fraction of 0.87. The NERVA and RFNTR were assumed to weigh 5 metric tons each, and additionally require tankage stages filled with hydrogen fuel, with each tankage stage having a mass fraction of 0.83. Aerobrake masses were taken as 0.15 of the maximum masses required to be decelerated.

Given these scenarios and upper stages, the results of the study are given in Table 2. below.

In table 2. all masses are given in metric tons. It can be seen that there are numerous mission architectures where an initial manned Mars mission can be accomplished with a single launch of the STS-Z (125 MT to LEO capacity) or ALS (100 MT to LEO), and even several where an initial mission can be accomplished with a single STS-C (80 MT to LEO) flight. Furthermore, repeat missions (whose requirement is given in the "expended mass" lines in table. 2) in many scenarios can be accomplished with a single refueling flight by an STS, a Titan IV Upgrade, or an STS-C. This is in marked contrast with current NASA Code-Z/Office of Exploration mission plans, which are based on orbiting motherships, and cryogenic propulsion for interplanetary transfer and landing vehicles (NASA Office of Exploration, 1988)[6]. Such plans involve from 700 to well over a thousand metric tons of propellant per mission, requiring 6 or more STS-Z launches per mission! Furthermore, despite their enormous cost and complexity, such mission plans leave the astronaut-explorers relatively impotent to accomplish much in the way of either exploration or development, as their cryogenic landing vehicle will necessarily restrict their visit to one site, and they lack a substantial source of electric or thermal power.

If an unmanned Mars Rover Sample Return (MRSR) is contemplated in place of a manned Mars mission, then the NIMF can be scaled down from 40 MT to 8 MT, and the masses given in Table 2 scaled down by a factor of 5 accordingly. It can thus be seen that there are numerous scenarios where a MRSR mission can be accomplished with a single launch of the current STS (25 MT to LEO capacity) or Titan IV (20 MT to LEO). Such a NIMF MRSR mission would be far superior to the conventional MRSR concept, as it would be able to deliver 2 MT of scientific payload to Mars, collecting samples and leaving behind roving instrument packages at numerous sites all over the planet. In a single one-launch mission, the NIMF MRSR would thus accomplish exploration work equivalent to that which would otherwise require perhaps a dozen conventional MRSR missions, and simultaneously prove in active field service the technology for full scale manned NIMF vehicles to follow.

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Table 2

ALTERNATIVE SCENARIOS FOR NIMF MANNED MARS MISSIONS

	Scen. 1	Scen. 2	Scen. 3
Cryo OTV			
Mission Mass	106	199	495
Expended Mass	66	154	445
NERVA			
Mission Mass	73	100	145
Expended Mass	33	53	100
RFNTR			
Mission Mass	64	80	104
Expended Mas	24	33	59
NIMF Mass Ratio			
CO_2 Propellant	8.3	3.8	5.6
H_2O Propellant	5.4	2.9	4.0
CH_4 Propellant	2.9	1.9	2.3

The conventional mission plans Code-Z is currently examination offer little potential for human exploration of the Red Planet, and none at all for sustaining a human presence there. By contrast, the one-launch mission architectures made possible by combining the NIMF with a hydrogen fueled nuclear thermal orbital transfer vehicle (either NERVA or, better yet, the RFNTR), will allow ready, repeated, and inexpensive access to Mars, and will open up a new world to human colonization.

THE NIMF AND THE ISSUE OF GLOBAL ACCESS FOR MARS EXPLORATION

A key requirement for any space transportation architecture designed for the exploration of Mars is that it be able to achieve "global access," which means planetwide mobility for scientific exploration and for long distance transportation of indigenous materials.

In the past, it has been frequently suggested[2] that the mission of global access could be performed by a chemical rocket ballistic hopper burning CO and O2. It is useful, therefore, to draw up a list comparing the merit of such as system to the NIMF in performing this mission.

1. Both the NIMF utilizing CO2 propellant as a working fluid and the chemical vehicle burning CO and O2 obtain a specific impulse in the neighborhood of 280-290 seconds. Neither engine is developed technology today, but the physical principles underlying both are well understood, and there is every reason to believe that either could be developed if appropriate amounts of development funds were available. In these respects the NIMF and the chemical vehicle are equals.

2. The NIMF can acquire propellant by compressing it out of the martian atmosphere at an energy cost of about 84 kWe-hrs per ton. The CO/O2 fuel for the chemical vehicle must be

produced by a chemical processing facility on the surface of the planet at energy cost of about 10,000 kWe-hrs per ton. In this respect, then, the NIMF is over a hundred times superior to the chemical vehicle. Indeed, opting for the chemical vehicle might be compared to buying a car which can only use gasoline costing $100.00 per gallon. Actually however, the situation is worse than that, because in this case you also have to buy not only the gas, but the gas station, and the oil company too. That is to say, the chemical vehicle will not be able to operate until there is a manned base with a nuclear reactor and a significant chemical engineering capability. In other words, no long distance exploration will be possible until after the infrastructure is built. Furthermore, even after the infrastructure is built, the production of fuel for the chemical exploratory vehicle will be an overhead on the base power supply that will be in competition with other demands that may frequently shove it aside.

3. The chemical vehicle must be fueled at a base (THE base) while the NIMF can fuel itself. This means that when the chemical vehicle takes off it must carry sufficient fuel for both the outbound and return trips, whereas the NIMF need only carry sufficient propellant for the hop one way. In effect, this difference in operating cuts the real specific impulse of the chemical vehicle in half relative to the NIMF, which in turn severely limits its operating range.

In the table below we give the mass ratios for both a NIMF and a chemical ballistic hopping vehicle, assuming that both use parachute assisted landing leaving a terminal rocket deceleration requirement of 500 m/s. (If parachutes are rejected in favor of pure rocket deceleration, then the NIMF performance degrades to levels somewhat superior to those given in the table for the chemical vehicle, while the chemical vehicle performance degrades to the point where it is completely unusable for hops beyond 300 km.)

Table 3

COMPARISON OF CAPABILITY OF NIMF AND CHEMICAL MARS HOPPERS

Hop Range (km)	NIMF Mass Ratio	Chemical Veh. Mass Ratio
281	1.72	2.98
676	2.07	4.28
1266	2.48	6.16
2240	2.98	8.86
3911	3.57	12.75
8000	4.28	18.34
Orbital	4.61	21.21

Now that mass ratio of 8.86 given for the chemical vehicle for a 2240 km hop is pretty sporty, it is slightly higher than the mass ratio of a Centaur upper stage vehicle (an aluminum balloon) carrying ZERO payload. A chemical hopper with this mass ratio might be able to exist and carry a tiny payload (because CO is denser than the Centaur's hydrogen fuel) but that is the absolute limit, and for practical purposes we may take the chemical vehicle's effective range at about 1300 km (810 miles). That is hardly global access. The NIMF, on the other hand, can easily reach any point on the planet in a single hop. Thus we see that in this respect the NIMF is infinitely superior to the chemical vehicle in that it can satisfy the essential mission performance requirements, whereas the chemical vehicle cannot.

4. Because of its lower performance, the chemical vehicle will have to be built much lighter and carry much less payload than the NIMF. This means that it will be structurally less safe, carry less scientific instruments, less supplies, and have less endurance for an extended visitation to an exploratory site than the NIMF. It also means that the chemical vehicle is completely incapable of performing any role in global transport of indigenous materials (such as transporting water from the martian polar cap to a base at the equator, or bringing a useful high grade ore from a distant mining site to the base), while the NIMF can do the job.

5. The NIMF carries its own source of electrical power, whereas the chemical vehicle does not. This means that the NIMF can recharge the hydrogen/oxygen fuel cells for electric land roving vehicles used locally by the exploration party, while the chemical vehicle cannot recharge its land rovers. The poverty of electric power faced by a group of explorers utilizing the chemical vehicle my also limit the use of their instruments, and together with their small supply capability, may put them in peril if a minor malfunction should delay their intended return to base.

6. The CO2 carried by the NIMF is a storable monopropellant under martian conditions, while both the CO and the O2 carried by the chemical vehicle are cryogens, and would boil off over time. The boiloff of these cryogenic propellants would itself limit the stay time of the chemical vehicle at an exploratory site. If the boiloff outgassing or other leakage were to occur in any enclosed space (for example that created by an attempt to vacuum jacket the tanks to reduce heat leak or an enclosing fuselage to reduce aerodynamic drag) a flammable (possibly explosive) and toxic mixture would result.

7. When the chemical vehicle returns to base it must land in the immediate vicinity of the fueling station or it will become useless, as there will be no way to haul it overland through the rough martian terrain if it lands a kilometer or two away. As the vehicle must use a parachute to assist in landing, and martian winds can be high, the chemical vehicle's requirement for precision landings may prove difficult or impossible to meet. The NIMF, on the other hand, can land anywhere. If it is only off by a few kilometers the astronauts can walk or return to bases by rover, if it is hundreds of kilometers off, it can just pump itself some more fuel out of the atmosphere and make an additional hop to get home.

8. Highly versatile non-ballistic supersonic winged aircraft configurations are possible for the NIMF. Because of weight limitations, such configurations are not viable for the chemical vehicle. Because the NIMF propellant is the atmosphere itself, in flight propellant acquisition systems are also possible. Such systems are out of the question for a chemical vehicle.

9. Because it refuels after it lands, the NIMF can land empty of fuel. The chemical vehicle, on the other hand, must land filled with enough fuel to return home. This means that it is much heavier than the NIMF when it is landing, putting increased demands on the engineering of its parachute deceleration system. If it hits the ground hard enough to crack its fuel tanks, it may explode.

10. Set against all these advantages for the NIMF is the fact that the NIMF carries a nuclear reactor. However the NIMF reactor carries a radioactive inventory about 6 orders of magnitude less than a power reactor, which will not only be a relief to the Martian EPA, but eliminates the central engineering headache of nuclear reactors, to wit the possibility of meltdown caused by radioactive decay heat if cooling is lost. This small radioactive inventory represents a small hazard compared to that presented by the chemical alternative

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to the NIMF, which will be virtually a flying bomb, a lightly built structure filled to the gills with toxic gas and chemical high explosive.

To summarize, if you want to explore, you have to have an exploratory vehicle, a self contained world that is free to roam at will. The great voyages of exploration of the 15th through 19th centuries were only possible because of the long range capability, independence, endurance and versatility of the full rigged sailing ship. If Columbus had had a coal fired steam paddle wheeler he never would have made it to America. The NIMF like the Santa Maria, the Endeavour, and the Beagle before it, derives her motive power from the air about her, and thus must it ever be with true explorers.

MISSION TO TITAN

Titan, Saturns's largest moon, possesses an abundance of all the elements necessary to support life. It is believed by many scientists that its chemistry may resemble that of the Earth during the period of the origin of life, frozen in time by the slow rate of chemical reactions in a low temperature environment. The abundant prebiotic organic compounds comprising Titan's surface, atmosphere and oceans may one day provide the resource base for extensive human settlement. However, because of its thick cloudy atmosphere, the surface of Titan is not visible from space, and many basic facts about this world remain a mystery. Thus a mission that could bring back samples from various locations on Titan and also perform a low level aerial reconnaissance would be of immense scientific benefit. As we shall see, the NIMF can accomplish such a mission.

Titan's atmosphere is composed of 90% nitrogen, 6% methane, and 4% argon. The atmospheric pressure is 1.5 times that of Earth at sea level, but because of the surface temperature of 100 K the density is 4.5 Earth sea level. The surface gravity is 0.14 that of Earth,.and the wind conditions are believed to be light. However, the great unknown is the Composition of the surface. It may be rock or water ice, it may have methane lakes and rivers, or the entire world may be covered by a methane ocean. The presence of higher hydrocarbons and other organic compounds within the bodies of liquid methane is highly probable, but the precise chemical nature of the mixture is unknown. Hydrocarbon and ammonia ice may also exist. These facts help determine the strategy that the NIMF Titan Explorer (NIFTE) mission will adopt.

The NIFTE mission is initiated by lifting a 8 MT unmanned automated NIMF fueled with 10 MT of liquid hydrogen to LEO. Such a launch can be accomplished by either an STS , a Titan IV, or an upgraded Titan III. The NIMF uses the hydrogen propellant to generate a delta-V of 7.6 km/s, driving itself onto a 4 year trajectory to Titan. Arriving at Titan, the NIMF aerobrakes itself into the atmosphere, with an entry velocity of 6.2 km/s. Of the 8 MT arriving at Titan, 2 MT are scientific payload, 3 MT comprise a 300 MW engine and its shield, and 3 MT are devoted to vehicle structure and machinery. The NIMF Titan Explorer vehicle is depicted in fig. 4.

Because surface conditions are unknown, the NIMF will not land. Rather it will use atmospheric intake of propellant and aerodynamic lift to remain airborne. Such a mission strategy is uniquely appropriate to Titan, as, with its thick atmosphere and light gravity, this world is the aviation paradise of the solar system. In fact, a human being standing on the surface of Titan would be able to fly by strapping wings onto to arms in the manner of Daedalus and Icarus (and this will no doubt be the preferred mode of transportation of the human settlers of Titan). More to the point, a 8 MT NIMF moving at 50 m/s (112 mph) would require a wing area of only 4 square meters to remain aloft. (i.e. no wings at all)!

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- **Engine plus Internal Shield** 2 MT (300 MWth)
- **External Shield** 1 MT
- **Structure and Machinery** 3 MT
- **Scientific Payload** 2 MT

- **Earth Departure Propellant** 10 MT Hydrogen
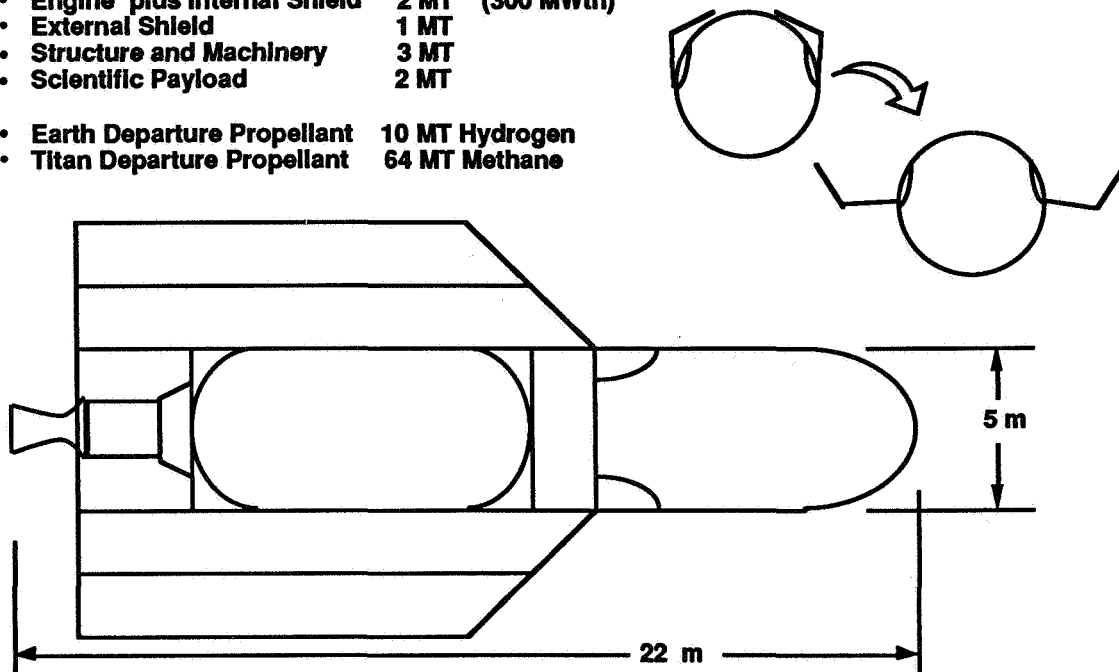- **Titan Departure Propellant** 64 MT Methane

5 m

22 m

Figure 4   The NIMF Titan Explorer (NIFTE) vehicle

Since fold-out wings of about 100 square meters can be easily accommodated within the payload fairing of the Titan IV, the NIMF Titan Explorer will be able to cruise as slowly as 20 mph, performing a leisurely low-level aerial reconnaissance of the entire satellite.

As it cruises along, the NIMF Titan Explorer will use small electric (battery or RTG) powered aircraft to collect samples from the atmosphere, surface,and submarine regions. These electric aircraft, which we cal TERNs (for Titan Explorers and Retrievers to NIMF) would mass about 10 kg each and could take the form of helicopters, fixed wing tilt rotor seaplanes, dirigibles, or even diving submarines, capable of both aerial flight and subsurface travel in the methane ocean (the low gravity, thick atmosphere, and low density of liquid methane all contribute to making such a vehicle possible). As the NIMF titan Explorer carries a scientific payload of 2 MT, a large variety of TERNs could be carried (fig. 5), anticipating a variety of surface and subsurface conditions, so as to ensure the success of at least several of these probes.

After Titan has been adequately explored and samples collected, the NIMF Titan Explorer will then address itself to investigating the remaining satellites in Saturn's system. Flying in Titan's atmosphere, the vehicle can acquire and liquify methane, which, as we have already noted, is an excellent nuclear thermal rocket propellant, yielding a specific impulse between 560 and 620 seconds. By filling its propellant tank with methane, the NIMF Titan Explorer can provide itself with sufficient propellant to generate a delta-V of 12 km/s. This is sufficient not only for a high energy return to Earth, but also for serial excursions for multiple sample collections from Saturn's other satellites.
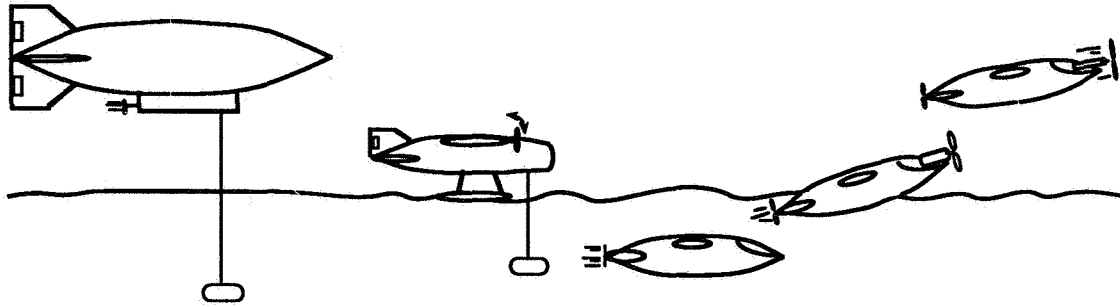
Figure 5 TERN Configurations. TERNs (Titan Explorers & Retrievers to NIMF) are battery or RTG powered miniature aircraft used to collect samples and data from the land, ocean, and submarine regions of Titan.

In Table 4. we show the delta-V's required for excursions from Titan to Saturn's other moons. Each excursion involves landing on the destination moon twice, collecting samples from two locations separated by up to 40 degrees of latitude or longitude, and then returning to aerobrake and refuel at Titan.

Table 4.

NIFTE VISITS TO SATURNS'S OTHER SATELLITES

Destination	Distance from Saturn (km)	Radius	Delta V Required (km/s)
Mimas	185,600	195	13.17
Enceladus	238,100	255	11.25
Tethys	294,700	525	10.05
Dione	377,500	560	8.60
Rhea	527,200	765	6.91
Titan	1,221,600	2575	0.00
Hyperion	1,483,000	143	3.84
Iapetus	3,560,100	720	6.90
Phoebe	12,950,000	100	8.33

It can be seen that with its delta-V of 12 km/s, the NIMF Titan Explorer can collect multiple samples from all of Saturn's moons except Mimas and bring them back to Earth.

MISSION TO JUPITER

Ganymede, Callisto, and Europa, three of the four Gallilean satellites of Jupiter, are all known to possess large amounts of water ice on their surface. Water can thus be used as a propellant for a NIMF vehicle intending to obtain multiple soil samples from each of these worlds. The NIMF Gallilean Explorer (NIFGE) mission we shall presently describe can accomplish this, and also perform a low altitude orbital reconaisance of all four of the Gallilean satellites (including Io), and perform flyby close inspections of all of the remaining moons of Jupiter.

Because of the absence of an atmosphere on the Gallilean satellites, this mission is in many ways more challenging than the NIFTE mission described above. In this case, a 4 MT NIMF Gallilean Explorer spacecraft (fig. 6) with 11.5 MT of hydrogen propellant and 1 MT of expendable tankage will be lifted to LEO by either an STS, a Titan IV, or an

upgraded Titan III. The NIMF will use the hydrogen contained in the expendable tank to generate a delta-V of 6.5 km/s, driving it onto a 2.7 year Hohmann transfer orbit to Jupiter. The NIMF uses oxide pellets coated with ZrC to protect them from hydrogen attack. After the Trans-Jupiter Injection burn, the expendable tank is discarded.

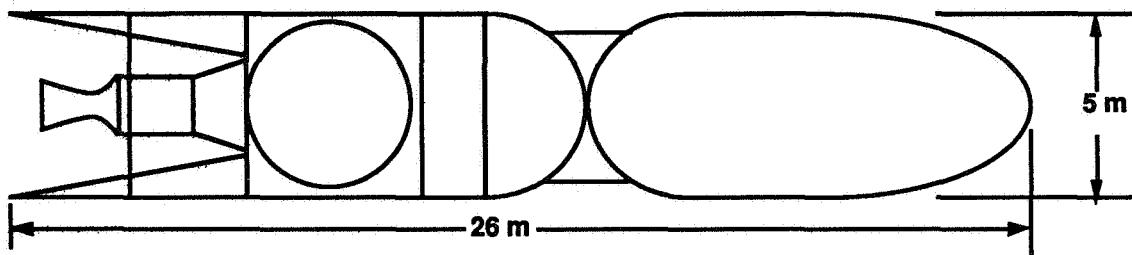|		
Engine plus Internal Shield	1.0 MT	(150 MWth)
External Shield	0.5 MT	
Structure and Machinery	1.5 MT	
Scientific Payload	1.0 MT	
Expendable Tank	1.0 MT	
Earth Departure Propellant	8.3 MT Hydrogen	
Callisto Landing Propellant	3.2 MT Hydrogen	
Callisto Departure Propellant	45.0 MT Water	

Figure 6 The NIMF Gallilean Explorer Vehicle.

Arriving at Jupiter, the NIMF uses the 3.22 MT of hydrogen contained in its internal tank to generate a delta-V of 5.3 km/s to go into low orbit around and then land on Callisto. The landing spot is chosen from orbit as one near a deposit of ice.

The NIMF then deploys treaded robots to go and collect soil samples. Other robots deploy a long double hose from the NIMF and insert it in an ice deposit. Steam generated by the NIMF reactor is then piped out of of hose to melt a subsurface pocket of ice, while the other hose pipes the resulting water back to fill the NIMF's internal fuel tank.

The internal tank can hold up to 45 MT of water propellant, which provides the NIMF with a delta-V capability of 8.6 km/s. This is sufficient to allow the NIMF to take samples from all over Callisto, to leave Callisto and land on Europa or Ganymede, or to take off Callisto for as medium energy orbit to Earth.

The NIMF Gallilean Explorer carries 1 MT of scientific payload, which is quite sufficient since only land robots are needed. However, during the visit to the ice-world of Europa, one additional instrument whose employment might be of great interest would be a small RTG powered miniature submarine, capable of melting its way through the ice to the water ocean that is believed to exist below. Data on what it finds there can be transmitted back to the NIMF by means of sound.

In Table 5. we show the delta-V's required to take off of either Europa or Callisto and land at a destination satellite of Jupiter.

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Table 5

JUPITER SYSTEM TRANSPORTATION DELTA-V'S

A. Departing from Europa

Destination	Distance from Jupiter (km)	Radius (km)	Delta-V Required (km/S)
Amalthea	181,000	103	11.95
Io	422,000	1826	5.81
Europa	671,000	1560	0.00
Ganymede	1,071,000	2500	5.65
Callisto	1,884,000	2450	6.88

B. Departing from Callisto

Destination	Distance from Jupiter (km)	Radius (km)	Delta-V Required (km/S)
Europa	671,000	1560	6.88
Ganymede	1,071,000	2500	5.86
Callisto	1,884,000	2450	0.00
Himalia	11,480,000	85	5.07
Elara	11,740,000	40	5.08
Lisithea	11,860,000	10	5.09
Leda	11,100,000	4	5.05
Ananke	21,200,000	10	5.24
Carme	22,600,000	10	5.24
Pasiphae	23,500,000	10	5.25
Sinope	23,700,000	10	5.25

It can be seen that with its delta-V capability of 8.6 km/s, the NIMF Gallilean Explorer can land on and collect samples from any Jovian moon found to possess ice, except Amalthea.

EXOTIC MISSIONS MADE POSSIBLE BY NIMF PROPULSION

In addition to its primary purpose as a facilitating technology for manned and large scale unmanned Mars missions, and unmanned sample return missions to the moons of Jupiter and Saturn, the NIMF concept is also an enabling technology for a number of exotic missions whose impossibility without the NIMF has caused them to be largely ignored by mission planners. For example, a winged automated NIMF utilizing atmospheric acquisition of CO_2 propellant could accomplish a Venus surface sample return, collecting ground samples and low level aerial reconaisance from every part of the planet before returning to orbit. Water ice exists on Uranus' moons Ariel, Umbriel, Oberon, and Titania, allowing NIMF sample return missions to target these destinations. Neptune's moon Triton could provide a ready source of methane propellant for NIMF exploration of the outer solar system. The asteroid Ceres has ice deposits on its surface, and it is believed that many other asteroids especially in the outermost belt and Trojan regions may also contain large amounts of water ice, thus giving water fueled NIMFs multiple bases from which to carry out the prospecting of the asteroid belt. NIMFs can extract propellant from the icy cores of comets, and could use comets as staging bases for missions to Pluto, the Oort Cloud, and beyond. If equatorial rotation is taken advantage of, the velocity required to attain Saturn orbit is 14.9 km/s, while that for Uranus or Neptune is 12.2 km/s. A winged hydrogen fueled NIMF with an Isp of 950 s could descend into the atmospheres of

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these planets and collect gas samples (or ground samples, if ground exists) refuel itself out of the hydrogen atmosphere, and reascend to orbit. A pure rocket (i.e. not jet augmented) NIMF would require a mass ratio of about 5.0 to accomplish this Saturn atmosphere return mission, while the mass ratio required for Uranus or Neptune atmosphere return would be about 3.7. It jet intake augmentation is used during thrust, these numbers could be substantially reduced.

CONCLUSION

We conclude that the NIMF concept offers great potential benefit for human exploration and colonization of the solar system. The NIMF opens up an enormous vista of possibilities, including the ability to launch a manned Mars mission in one launch, and economically sustain a permanent and large scale human presence on Mars. The NIMF vehicle further affords unlimited mobility for exploration not only of Mars, but the asteroid belt, and the satellite systems of the major planets as well. We recommend that the NIMF be made the subject of an in depth study and a substantial research and development effort.

Acknowledgments

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