

DEVELOPMENT OF A LONG-TERM EARTH-MARS CYCLING VESSEL

Jonathan A Greenspon *
And
Austin Albert Mardon, PhD **

ABSTRACT

Spacecraft developed for extended-duration cycling between the Earth and Mars can represent a direction toward development of a “clipper ship” for colonisation, exploration and transportation of personnel and cargoes using the same components for structure, shielding, coolant, and fuel as other ships and space platforms. This type of long-term, interplanetary spacecraft represents an extension not only of current technology, but also a means to create systems destined for service in terms of years, which is a critical parameter for optimising the performance of interplanetary and potential interstellar spacecraft.

A quantitative analysis is presented of the kinematics of a single stage interplanetary cycling ship. In the limiting case of a spacecraft on a continual mission with no deceleration at the either aphelion or perihelion, a dead-weight fraction of 10⁻³, with the bremsstrahlung velocity of 3.2m/s (providing a consistent 0.6-0.8 g of artificial gravity to its occupants) would enable “contact” between Earth and Mars on an average of every 275 days.

INTRODUCTION

For advanced space exploration missions, unusual requirements are levied on the structural components of the spacecraft. In many cases, the preferred solution is the utilization of innovative technologies. Spacecraft constructed to enable centrifugal rotation while simultaneously entering interplanetary transfer orbits can use the same material for structure, shielding, coolant, and fuel as conventional designs.

This type of adaptable configuration spacecraft achieves an extremely low dead-weight fraction (fraction of non-payload mass remaining after all fuel is expended), which is a critical parameter for optimising the performance of any interplanetary spacecraft. At the same time, volume and mass must be idealised in having a minimum weight of material while maximising habitable flexibility. This dead-weight consideration is even more important for a single-staged space going vessel.

* StarGate Research Laboratory – PI, Inc., Apple Valley, CA USA

** StarGate Research Laboratory – PI, Inc., Edmonton, Alberta, CANADA

Assume that we have a conventional bi-propellant (fuel/oxidiser) engine with a specific impulse in the region of 400 (technically 367 – 425); the details are left to the engineers. Assume that the spacecraft structural material is lightweight honeycombed aluminium and alloyed metallic composites. Assume a cycling trajectory with no deceleration at either planet, although with a propellant reserve that would permit orbital braking and entry.

Then, as we shall see in the section on kinematics, appreciable burnout velocities can be achieved if we can keep the dead-weight fraction as low as 10⁻³, i.e. only one-third of non-payload mass remains after all fuel (reserve fuel notwithstanding) is expended. For example: in the limiting case of a cycling spacecraft, if the payload fraction is 10⁻³, then the final burnout velocity is 3.2 m/s, would get the spacecraft in a roughly 500 day solar orbit.

A quantitative analysis is presented of the kinematics of interplanetary cycling spacecraft. A particular rotating ring interplanetary cycling ship is calculated. Future research considerations are outlined. Summary and conclusions are presented.

DESIGN OF A PRELIMINARY CYCLING SPACECRAFT

First proposed in the early 1950's¹, cycling spacecraft permits the fundamental recurrent transfer between our home world and Mars, without cessation of transit, of personnel and cargoes in a continuous pattern. By adding ancillary benefits, as detailed below, including using the platform as an on-going space research laboratory in solar orbit to study the sun, as well as extra-solar objects of interest and "University" for long-range space sensors. Both NASA and the National Commission of Space² expanded this idea in the mid 1980s. StarGate Research Laboratory is currently preparing to investigate the concept of spacecraft constructed to rotate and simultaneously provide a stable, core element using the same components and materials for structure, shielding, coolant, and fuel as more conventional orbital space structures.

The ideal spacecraft can be lightweight, inexpensive, and efficient by using current developments in both structure and fuel. A critical form to consider is that this structural system will be called to serve in a "deep-space" medium for a period much longer than either MIR or the International Space Station because of the role designed for the cycling spacecraft. The platform can be readily adapted, though, to provide for expansion and/or reconfiguration during its lifetime with the admixture of open space pallet mount locations, or various interior partitions.

Tankage areas for hydrogen/oxygen (or any other fuel/oxidiser) first serve as fuelling regions, then are capable of venting/purging, and conversion to habitable spaces. In this way, almost all essential parts of the spacecraft are used during the operational lifetime of the craft. This type of redevelopmental spacecraft achieves an extremely low dead-weight fraction, which is a critical parameter for optimising the performance of interplanetary cycling spacecraft.

The radiation shield and outer hull must be constructed/formed in such fashion as to enable a majority of normal operations to be conducted during periods of solar maximum activity. This includes the potential of meteoritic activity in the spacecraft's orbital path. A critical concern to space activity extending beyond the Earth's Van Allen belts is that once outside the protection of the belt zones, solar activity can rapidly radiate human tissue structures. Under these conditions, the crew must either be provided with a stable, radiation-resistant environment – either through over-development of the complete spacecraft or through the inclusion of a solar “shelter”. The anticipated crew/passenger complement tends to obviate the shelter philosophy.

The system as a whole as conceived by includes:

- (1) A despun or despinnable docking location for auxiliary spacecraft,
- (2) A thermally insulated habitat region,
- (3) A rotational structure not exceeding vestibule limitations of the human inner ear,
- (4) An adaptable and augmentable communications/data/electronic power system,
- (5) Long-term independent operational and maintenance functionality, and
- (6) A guidance/navigation/attitude control capability that is operable while rotating or in a non-rotational mode.

The attractive attributes of the system include: Unitised design – current modules and technologies can functionally serve as, propellant, shielding, structure, power source, and support during launch or operational modes; long lifetime in Earth-Mars-Solar orbit; low cost material (nothing more exotic than current aerospace applications materials is necessary); low cost fabrication (development has already been performed into the basic structural concepts); low launch cost (high, long-duration acceleration forces aren't needed).

Other possible avenues to usefulness emphasize the orbital properties of the spacecraft, distance and direction from Earth's abundant microwave and electromagnetic signature, controllable gravity alteration capabilities, and a wide range of capabilities for embedded avionics, including: multi-phase radio, and long-term power generator/storage, and guidance and control.

As the authors extend the concept, individual modules can be orbited by boosters, and later assembled into a large spacecraft. This technology is readily demonstrated through the MIR and ISSA development. Once assembled, the low accelerations from any typical propulsion would not endanger the structural or tensile strength of the structural framework.

Suggested space exploration missions including: (1) solar research station, (2) extraterrestrial signal monitor, (3) interferometry observatory, (4) operational radar mapping of Earth orbit crossing bodies, (5) manned Mars mission support, (6) commodities transfer and storage for interplanetary actions.

KINEMATICS

Cycling spacecraft constructed from common usage components use the same material as current designs (ISSA, MIR, Spacelab, etc.) for structure, shielding, coolant, and fuel, but more importantly, from the kinematic viewpoint, that means that very little of the spacecraft's mass is designed to be wasted as non-productive non-payload.

This type of adaptable configuration spacecraft achieves an extremely low dead-weight fraction (fraction of non-payload mass remaining after all fuel is expended), which is a critical parameter for optimising the performance of any interplanetary spacecraft. At the same time, volume and mass must be idealised in having a minimum weight of material while maximising habitable flexibility. This dead-weight consideration is even more important for a single-staged space going vessel.

The equations of the Hohmann ellipse have been used for the kinematic calculations in this paper. These include the correct relationship first given by Hohmann between initial point velocity at perihelion (V_p) and Delta V relative to Earth distance R_2), and between time necessary for the transfer (T), namely:

$$V_p = \sqrt{2 * G * M_s * \frac{R_1}{R_2 * (R_2 + R_1)}} \quad T = \pi \sqrt{\frac{(R_1 + R_2)^3}{8Gm}}$$

For an interplanetary vehicle, the burnout fraction (χ) is the ratio of the rest mass of the vehicle at burnout to the rest mass of fuel consumed:

$$\chi = M_b / M_f$$

And the rest mass of fuel consumed is the sum of the rest mass of fuel exhausted (M_{ex}) and the rest mass of fuel converted to kinetic energy:

$$M_f = M_{es} + (\epsilon)M$$

FUNDAMENTALS OF ROTATION

According to NASA studies³ in the 1970's, man can adapt to rotation rates of approximately 3 revolutions per minute, although recommendations by this study point to maintaining a rotation of 1 rpm (or less) if the personnel will be regularly transitioning between a 1 gravity, rotating environment, and a zero-gravity axial core command area. However, to maintain NASA's ideal of 1 revolution/minute, the habitat ring would need to be approximately 1600 metres in diameter. That developmentally limits the feasibility of developing and fielding a convenient Earth-Mars cycling spacecraft. For operational potentials to be exploited, a more compact 110 or 200 metre in diameter habitat unit is envisioned. In this size, rotated at a sedate 2 revolutions per

minute, the vehicle in question would provide its occupants with an acceleration of 4.9 - 6.57 metres/second (.5 - .67 G).

With low accelerations, little structural strength is required, hence the plausibility of a rotational structure on a despun core. "Will the ring's structure stand up to even 1/20g? If not, the final velocity will be lower". Questions that arise however are fundamental needs of research for this system to be deployed.

- (1) How are liquids and consumable items to be transferred between a rotating ring and a non-spinning axial core? If the core module is designed with a central access way, then all connection points for such transfer will need to be made across non-centralised plumbing.
- (2) What difficulties will be encountered with the movement of commodities and crew from point to point within the spacecraft? Over eleven years, MIR has maintained studies of this centre-of-gravity interaction; however, this is a stationary facility – not a rotational habitat.
- (3) What problems will be inherent to attitude control and reaction thrust across the structure? Mounting RCS systems outboard, on the ring, would be beneficial, as this extends the "arm-length" of the RCS activity. However, a system must be incorporated to permit operation of the RCS equipment – WITHOUT the requirement of despinning the ring.
- (4) What precautionary measures or equipment will be necessary for the use of a cycling spacecraft? When a situation arises aboard a space station or the shuttle, help is nominally within 24 hours. Not so with a Mars or interplanetary facility.

Obviously, certain scenarios, such as the development of independent life-support, food supplies, etc. would be most beneficial, although not necessary for implementation of this concept.

FUTURE RESEARCH

This paper is a conceptual study, backed by quantitative analysis. Future research is needed to develop the concept into the systems design phase. The following are some of the important considerations yet to be performed:

- Geometry: Should the spacecraft be an axial core configuration with an independent rotating ring, a axial configuration with a series of modules extended outward on "spokes", or a more conventional axial/ring configuration, using the axis of the core as a rotation point?
- System Interrelation: How are the modules be configured in relation to each other, and how are they detached for upgrading or replacement? What forms of connectivity are applicable to rotational or stationary-rotational module interconnects?
- Fuel: What are the short and long-term fuel/oxidiser requirements; how should the fuel be stored for ready usage? Will cryogenic fuels be more effective over the long-term than hypergolic or monopropellants? If detachable tankage is used, should it be in unitised pack-

ages (each tank holding fuel and oxidiser) or separated via independent tanks? How will it be pumped or introduced into the reaction chamber?

- Centroid: As modules are used and personnel are moved, the center-of-mass of the spacecraft shifts. How is attitude corrected to maintain the proper thrust vector? What is the net effect of the structure rotation to center-of-mass options?
- Radiation: How much can the spacecraft payload be hardened against nuclear and cosmic radiation by redundancy and self-repair methods?
- Parameters: What are specific parameters of mass and thrust for selected configurations of cycling spacecraft and rotation or crew/cargo manifests? What forms and determinations are necessary for auxiliary craft operations and deployment?
- Braking: Can the cycling spacecraft be decelerated at the either end for orbital entry? What deflection is necessary to return to cycling operations after orbital activities?
- Cost: What does such a spacecraft cost?
- Schedule: When is such a spacecraft likely to be feasible; what precursor missions are likely (i.e. Mars Direct, Lunar Return, First Lunar/Mars Outposts, etc.)? How does cycling spacecraft development fit in with other aspects of space transportation infrastructure?

Many basic questions remain. The authors hope that the Earth-Mars cycling spacecraft concept itself stimulates interesting answers.

SUMMARY AND CONCLUSIONS

Spacecraft constructed for generated gravitation cycling between planets within the solar system can use the same materials for structure, shielding, coolant, and fuel as conventional space structure designs. To reduce the non-essential weight/mass factors, a particular self-reliant structure must be developed for Earth-Mars orbital operations, extending to interplanetary applications.

Ordinary fuels and/or oxidisers can efficiently serve an ideal fuel for power and propulsion. Advances being made for the International Space Station, as well as those previously developed for the Space Transportation and MIR projects have many cases of suitability for cycling ship applications. Other developments are considered relevant to cycling potentials, including advanced propulsion techniques, closed loop life support systems, space environment medical advances, and radiation defence within the space environment. Specific situations related to the development of rotational habitats are discussed in terms of spin/despin, centripetal/centrifugal forces, simulated gravity levels, and structural stability.

This paper is a conceptual study, backed by quantitative analysis. Future research is needed to develop the concept into the systems design phase. There are some important considerations yet to be performed, involving Geometry, System Interrelation, Fuel, Centroid, Radiation, Parameters, Braking, Cost, and Schedule.

CITED REFERENCES

¹ Von Braun, Wernher, *Das Mars Projekt*. University of Illinois Press, Urbana, 1953.

² National Commission on Space. *Pioneering the Space Frontier*. The Report of the National Commission on Space, Bantam Books, New York, 1986.

³ National Aeronautics and Space Administration. *Space Settlements, A Design Study*. NASA Publication SP-413.