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Conventional and Bimodal Nuclear Thermal Rocket (NTR) Artificial Gravity Mars Transfer Vehicle Concepts

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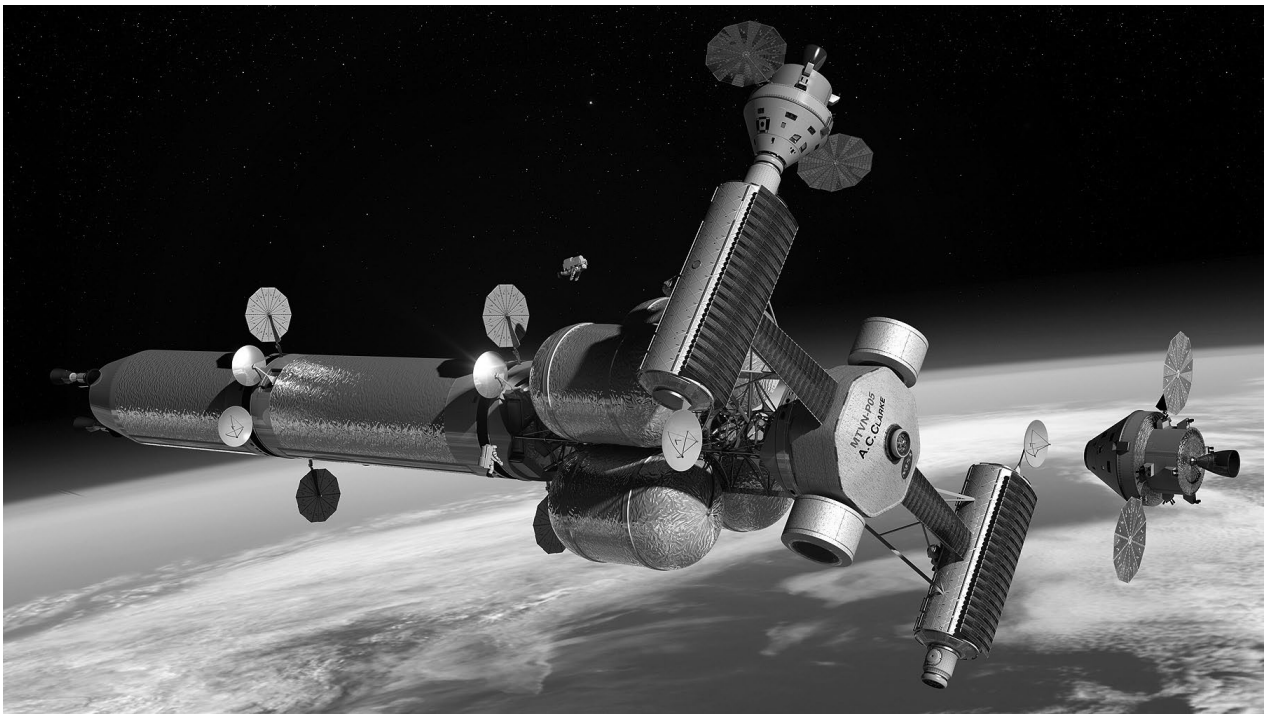

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Abstract

A variety of countermeasures have been developed to address the debilitating physiological effects of zero-gravity (0-g) experienced by cosmonauts and astronauts during their ~0.5 to 1.2 year long stays in low Earth orbit (LEO). Longer interplanetary flights, combined with possible prolonged stays in Mars orbit, could subject crewmembers to up to ~2.5 years of weightlessness. In view of known and recently diagnosed problems associated with 0-g, an artificial gravity (AG) spacecraft offers many advantages and may indeed be an enabling technology for human flights to Mars. A number of important human factors must be taken into account in selecting the rotation radius, rotation rate, and orientation of the habitation module or modules. These factors include the gravity gradient effect, radial and tangential Coriolis forces, along with cross-coupled acceleration effects. Artificial gravity Mars transfer vehicle (MTV) concepts are presented that utilize both conventional NTR, as well as, enhanced bimodal nuclear thermal rocket (BNTR) propulsion. The NTR is a proven technology that generates high thrust and has a specific impulse (I_{sp}) capability of ~900 s—twice that of today's best chemical rockets. The AG/MTV concepts using conventional Nuclear Thermal Propulsion (NTP) carry twin cylindrical International Space Station (ISS)-type habitation modules with their long axes oriented either perpendicular or parallel to the longitudinal spin axis of the MTV and utilize photovoltaic arrays (PVAs) for spacecraft power. The twin habitat modules are connected to a central operations hub located at the front of the MTV via two pressurized tunnels that provide the rotation radius for the habitat modules. For the BNTR AG/MTV option, each engine has its own closed secondary helium (He)-xenon (Xe) gas loop and Brayton Rotating Unit (BRU) that can generate 10s of kilowatts (kW_e) of spacecraft electrical power during the mission coast phase eliminating the need for large PVAs. A single inflatable TransHab-type habitation module is also used with multiple vertical floors oriented radial to the MTV spin axis. The BNTR MTV's geometry—long and linear—is naturally compatible with AG operation. By rotating the vehicle about its center-of-mass (CM) and perpendicular to its flight vector at ~3.0 to 5.2 rpm, a centrifugal force and AG environment corresponding to ~0.38 to 1.0 g can be established to help maintain crew fitness out to Mars and back. Vehicles using NTP/ Bimodal Nuclear Thermal Propulsion (BNTP) can more readily accommodate the heavier payload mass and increased RCS propellant loading associated with AG operation, and can travel faster to and from Mars thereby reducing the crew's exposure to galactic cosmic radiation and solar flares. Mission scenario descriptions, key vehicle features and operational characteristics for each propulsion option are presented using the lift capability and payload volumes estimated for the Space Launch System (SLS)-1B and follow-on Heavy Lift Vehicle (HLV).

1.0 Introduction and Background

In the 2033 to 2035 timeframe, human exploration missions to Mars could begin provided there is a true national / international commitment to this endeavor that is backed up by realistic, sustained funding necessary to develop the critical technologies needed to make this dream a reality (Ref. 1). Initial missions could be orbital precursors used to check out the key components (e.g., the propulsion and life support systems) of the MTV. Such a mission would require ~18 months in a 0-g environment with the crew spending ~60 days in Mars orbit. Follow-on landing missions could expose the crew to Mars gravity (~0.38-g) for long periods (up to ~18 months) plus 6-month transits to and from Mars in 0-g. In the event of an abort back to orbit during or shortly after landing (Ref. 2), the crew could be subjected to ~2.5 years of weightlessness aboard the MTV. In view of the known debilitating physiological effects (Ref. 3) associated with prolonged exposure to 0-g, and recent emerging health concerns such as VIIP syndrome (Ref. 4), an AG spacecraft using NTP offers many advantages (including reduced trip times) and may indeed be an enabling technology for future human flights to Mars and beyond.

A variety of AG/MTV concepts were developed by the Martin Marietta Astronautics Group for NASA's Mars Exploration Case Studies (Refs. 5, 6, and 7) in 1988 to 1989. Each of these concepts used a large diameter (~39 to 46 m) aerobrake (AB) with a low lift to drag (L/D) ratio of ~0.2 for Mars orbit capture (MOC). These large ABs required assembly in LEO before being outfitted with habitation, auxiliary PVA power and chemical propulsion system elements within their protective envelope. By rotating the AB about its central axis at different spin rates and mounting the habitat modules near the outer perimeter of the AB to increase the rotation radius, a range of centrifugal forces can be generated for the crew during the transit out to Mars and back. A sampling of these AB concepts (minus their multiple expendable trans-Mars injection (TMI) stages) is shown in Figure 1.

Concept 1 was developed for a large crew of 12 to 18 astronauts. It carried eight cylindrical Space Station Freedom (SSF)-type habitation modules arranged in a ring to provide a 100 m long circular jogging track. The modules were mounted to a large 45.6 m diameter AB sized for aerocapture (AC) at both Mars and again at Earth for spacecraft recovery and possible reuse. This very large spacecraft had an initial mass

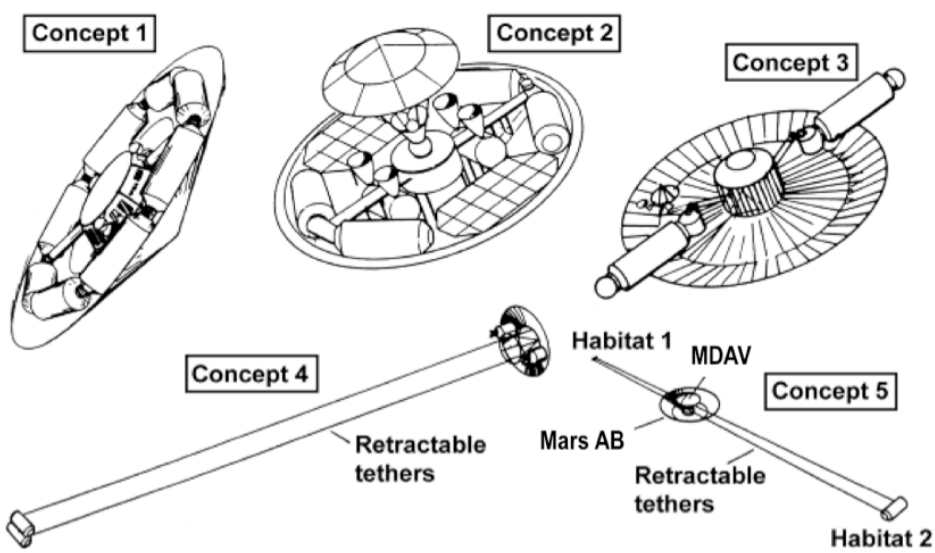

Figure 1.—AG/MTV Concepts Using Aerobraking, Chemical Propulsion and Tethers (Ref. 8)

in low Earth orbit (IMLEO) > 1500 metric tons (1 t = 1000 kg). Concept 2 carried eight astronauts and used four SSF habitat modules arranged in a Bent-I configuration inside a 41 m diameter AB. Two pressurized tunnels connected the four habitat modules to a central logistics and docking hub to which the Mars Descent/Ascent Vehicle (MDAV) was attached. The IMLEO for Concept 2 was ~1091 t. Concept 3 utilized a deployable flexible fabric AB (~39 m in diameter) and carried two cylindrical hab modules each with five separate floors arranged perpendicular to the modules' long axis. The modules were attached to the central logistics and docking hub using swivel joints allowing them to swing outward to increase their rotation radius during AG operation. The modules were cranked back inside the protective envelope of the AB prior to MOC. The modules housed five to seven crew and the total mission IMLEO was ~687 t including the four expendable TMI stages. Concepts 4 and 5 used dual retractable tethers to separate paired or individual hab modules from the AB and primary propulsion system. With tether lengths of approximately several hundred meters, rotations rates as low as 2 rpm could provide ~1-g of centrifugal acceleration for the crew.

Each of the above concepts had a number of drawbacks (Ref. 8). Concepts 1 and 2 were very large, required significant orbital assembly for the AB and overall vehicle, and had large in IMLEO requirements (>1000 t). Concept 3 required an internal arrangement for the hab modules that differed from that of the SSF habitation modules used in the other designs. It also required movement of two major pressurized mechanical joints. With tethered Concepts 4 and 5, the Reaction Control System (RCS) propellant requirements to initiate and stop vehicle rotation were large, and the dynamic control problems more severe during the deployment and retraction process, as well as during vehicle spin up and spin down. A tether break or reel freeze-up could also be a critical failure mode. From an operational standpoint, once deployed, the crew in Concept 4 would be isolated from the systems enclosed within the AB (e.g., MDAV) and in Concept 5, isolated from each other as well.

To avoid the deficiencies of the above concepts, Martin Marietta proposed Concept 6 (Ref. 8), an AG/MTV design that used chemical propulsion and carried twin cylindrical SSF habitation modules whose long axes were oriented perpendicular to the longitudinal spin axis of the MTV—referred to as the Dumbbell B configuration (Figure 2). The hab modules were connected to a central logistics and docking hub by two pressurized tunnels each ~12.5 m long. Each hab module—designed to accommodate two to three crewmembers—had excess capacity so that either could serve as a safe haven for the entire crew in case of an emergency. Attached to the Sun-facing side of each tunnel and hab module were ~30 and 75 m^2, respectively, of PVAs producing ~26 kW_e of electrical power for the spacecraft's various systems. Once fully assembled, the rotation radius from the center of the logistics module to the floor of each hab module was ~17 m allowing centrifugal acceleration levels ranging from 0.38-g to 0.68-g for vehicle spin rates of 4.5 to 6 rpm. At a slightly higher spin rate of 7.25 rpm, 1-g could be achieved. The pressurized logistics hub also provided a shirt-sleeve environment and anytime crew access to the MDAV docked to the front of the vehicle.

The aft end Mars orbit capture stage (MOCS) and forward trans-Earth injection stages (TEIS) used four ~25 klb_f liquid oxygen/liquid hydrogen (LOX/LH_2) RL10B-2 engines with an I_{sp} of ~460 s. The MOCS also functioned as the TMI stage using propellant supplied from six surrounding drop tanks jettisoned in pairs as they are drained. The vehicle IMLEO at TMI was ~710.8 t.

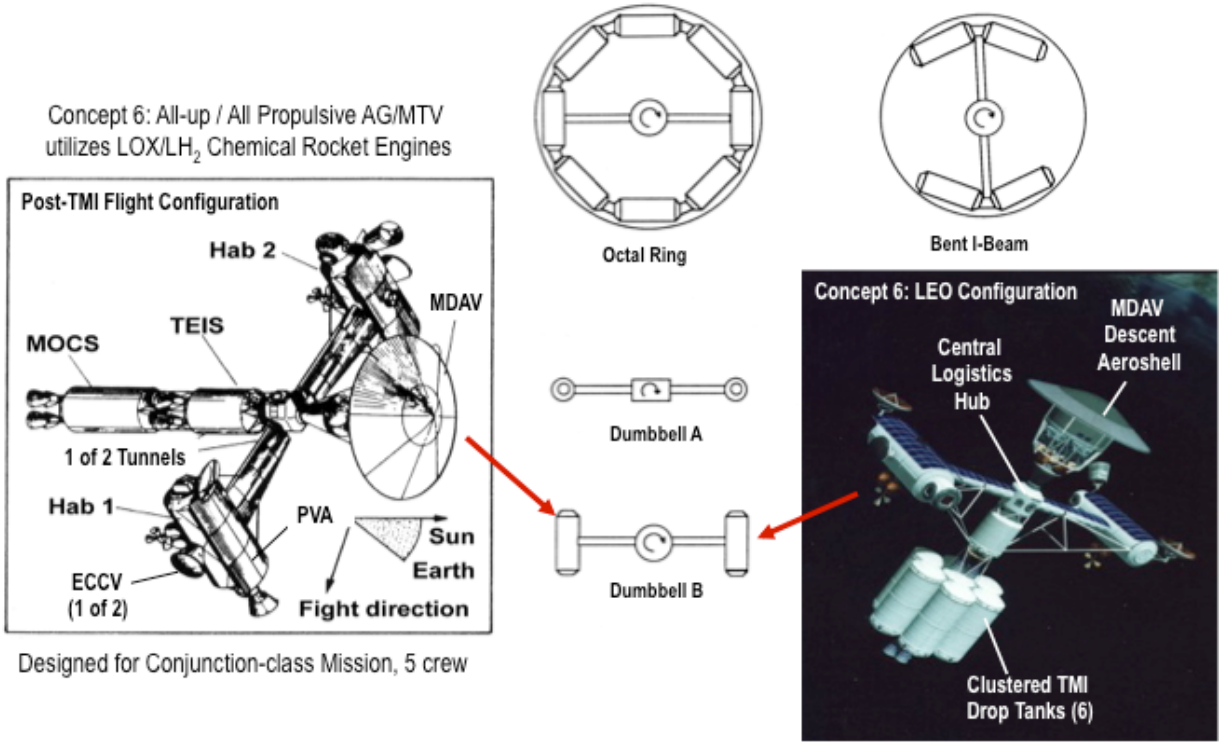

Figure 2.—Key Features and Components of the Concept 6 AG/MTV

In 1999, NASA Glenn Research Center (GRC) introduced to NASA's Design Reference Mission (DRM) 4.0 study an AG/MTV design that utilized BNTR propulsion (Refs. 2 and 9). DRM 4.0 featured a split mission approach with two minimum energy cargo flights used to pre-deploy orbital and surface assets at Mars ahead of the crew. The crewed MTV departed LEO ~26 months later and utilized a higher energy, fast conjunction trajectory out to Mars and back. Though the one-way transit times for the crew were short (~5 to 7 months), stay times at Mars were long (~500 days or more to allow proper realignment between Mars and Earth for the crew's return to Earth). In the event an aborted landing or major surface system failure shortly after landing forced an early return to the orbiting MTV, the crew could spend the entire mission duration (~2.5 years) in a weightless environment.

The BNTR AG/MTV, named *von Braun* and shown in Figure 3, eliminated this problem. With its bimodal engines providing both efficient high thrust propulsion and continuous 24/7 electrical power, the spacecraft no longer needed to deploy and operate large Sun-tracking PVAs, and its configuration—long and linear—was naturally compatible with AG operations. Following the TMI maneuver, the drop tank enclosed within the saddle truss was jettisoned in preparation for vehicle spin up. By rotating the vehicle about its CM and perpendicular to its flight vector (illustrated at the bottom of Figure 3), a centrifugal force and AG environment could be established to help maintain crew fitness during the transit out to Mars and back, also while in Mars orbit in the event of an abort-to-orbit.

The *von Braun* had an IMLEO of ~166.4 t (Ref. 9). Its core propulsion and power stage used three 15 klb_f BNTR engines. Each engine had its own 25 kW_e BRU operated at 2/3rd of rated power (~17 kW_e) to produce the 50 kW_e of total electrical power needed to run the crewed MTV. If an engine or BRU were lost, the remaining two units would be ramped up to 25 kW_e to produce the required power level. During the outbound transit to Mars, the *von Braun* rotated at ~4 rpm to produce a centrifugal acceleration of ~0.38-g. On the return leg, its rotation rate was increased to ~6 rpm to produce near Earth gravity conditions (~0.79-g). At a slightly higher spin rate of 6.8 rpm, 1-g was achievable.

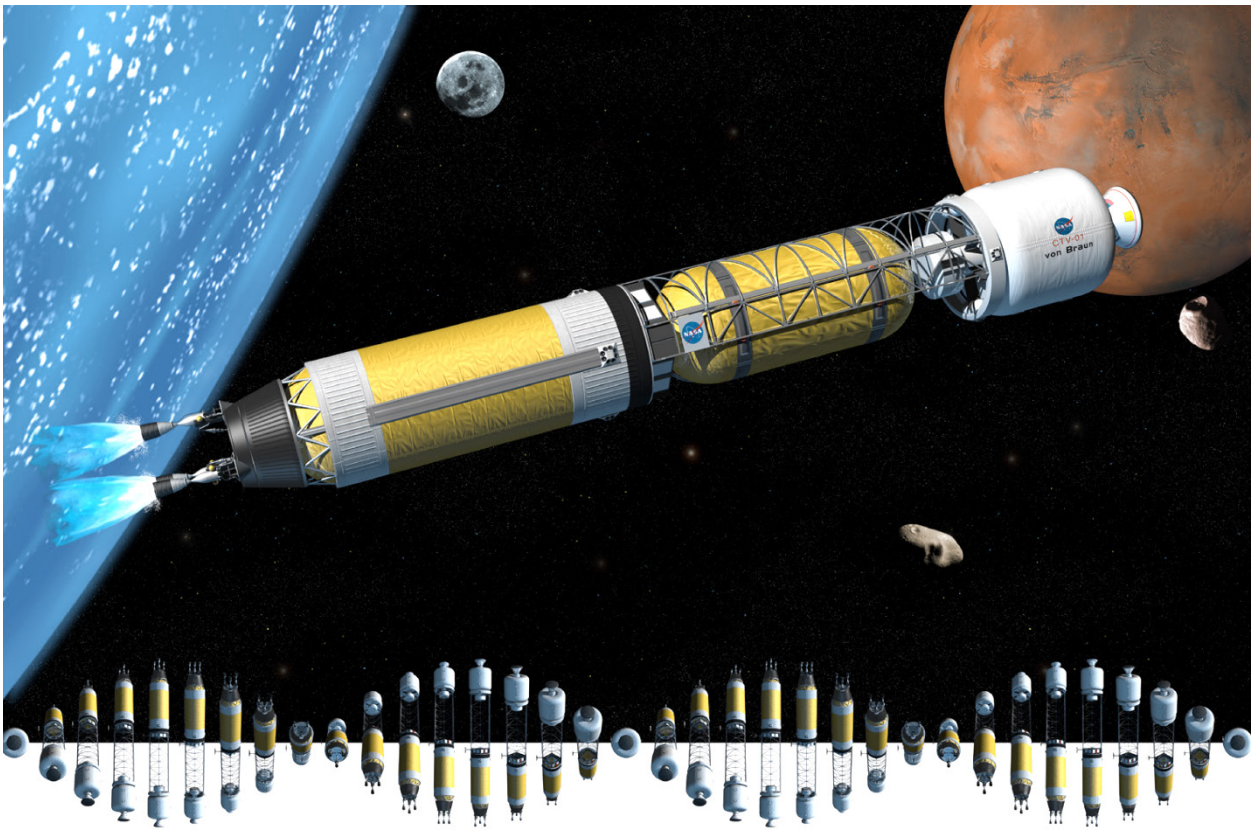

Figure 3.—Artificial Gravity BNTR Crewed MTV—Mars DRM 4.0 (1999)

In that same year (1999), an AG Workshop, sponsored by NASA and the National Space Biomedical Research Institute (NSBRI), was held in League City, Texas (Ref. 10). In the executive summary of Reference 10 it was recommended that NASA appropriate the necessary resources to initiate AG parametric studies both on the ground and in space. It also recommended that NASA establish an AG working group to monitor and assess progress being made in this area. Five years later, in 2004, the International Academy of Astronautics (IAA) set up a Study Group on AG and used as its starting point the set of questions and recommendations from the 1999 AG Workshop. The Study Group recognized that a combination of exercise and pharmaceuticals alone were unlikely to counter the anticipated effects of long-term crew exposure to the 0-g and partial-g environments of a Mars mission. So the question was again asked—Are rotating AG vehicles needed for Mars? Answering this question requires an understanding of the AG trade space and the relative importance of the physiological, medical, human factors, environmental, and engineering components that it includes. While acknowledging this larger picture, the Study Group's final report (Ref. 11) focused its attentions on the biomedical aspects of this trade space. It strongly recommended bringing back animal research to ISS in order to get early, in-fight data, also developing a space-based short-radius centrifuge as a means of assessing the effectiveness on humans of intermittent, short arm centrifugation inside a spacecraft.

In 2007 to 2008, NASA conducted another inter-center, multi-directorate study on the requirements and concepts needed for a human Mars mission. Known as the Mars Design Reference Architecture (DRA) 5.0 study (Ref. 12), its purpose was to provide an update to the earlier DRM 4.0 study conducted in 1999. Both short and long surface stay landing missions were considered and the fast conjunction long stay option was again selected because it provided sufficient time at Mars for the crew to explore the planet's rich geological diversity while also reducing the crew's transit times to and from Mars to ~6 months, or ~1 year

in deep space. A variety of propulsion options were also proposed—chemical, NTP, solar and nuclear electric propulsion (SEP/NEP)—but only chemical and NTP were considered because of their maturity and their ability to provide short transit times.

The NTR was ultimately selected as the propulsion system of choice for DRA 5.0 because of its high thrust and high I_{sp} capability (100 percent higher than today's best chemical rockets), its increased tolerance to payload mass growth and architecture changes, and its low IMLEO important for reducing the HLV launch count, overall mission cost and risk. More importantly, the NTR is a proven technology and the only advanced propulsion option to be successfully ground tested at the performance levels required for a human mission to Mars. No large technology or performance scale-ups are needed as with other propulsion options. In fact, the smallest and highest performing engine tested during the Rover / Nuclear Engine for Rocket Vehicle Application (NERVA) programs (Ref. 13)—the 25 klb_f "Pewee" engine is sufficient for a human mission to Mars when used in a clustered engine arrangement.

Like the earlier DRM 4.0 study, DRA 5.0 also selected a split mission approach using separate cargo and crewed MTVs. Both vehicle types utilized a common core NTP stage (NTPS) each with three 25 klb_f composite fuel Pewee-class engines. Two cargo vehicles were used to pre-deploy surface and orbital assets ahead of the crew who arrived during the next mission opportunity ~26 months later. The crewed MTV, shown in Figure 4, was called *Copernicus* (Refs. 12 and 14). It was a 0-g vehicle consisting of three basic components: (1) the crewed payload element; (2) the NTPS; and (3) an integrated saddle truss and LH_2 propellant drop tank assembly that connected the payload and propulsion elements. Four large PVAs supplied the spacecraft its electrical power needs.

Like the *von Braun*, *Copernicus* had attached to its TransHab module an exterior container carrying contingency consumables used to sustain the crew in the event of an early abort from the Mars surface. Unfortunately, AG vehicles were ground ruled out of the DRA 5.0 study so crew fitness onboard *Copernicus* after ~2.5 years in a 0-g environment was questionable. An AG version of *Copernicus*, called *Copernicus-B*, was developed by GRC shortly after the DRA 5.0 study was completed and it is one of several AG/MTV concepts that are discussed in this paper.

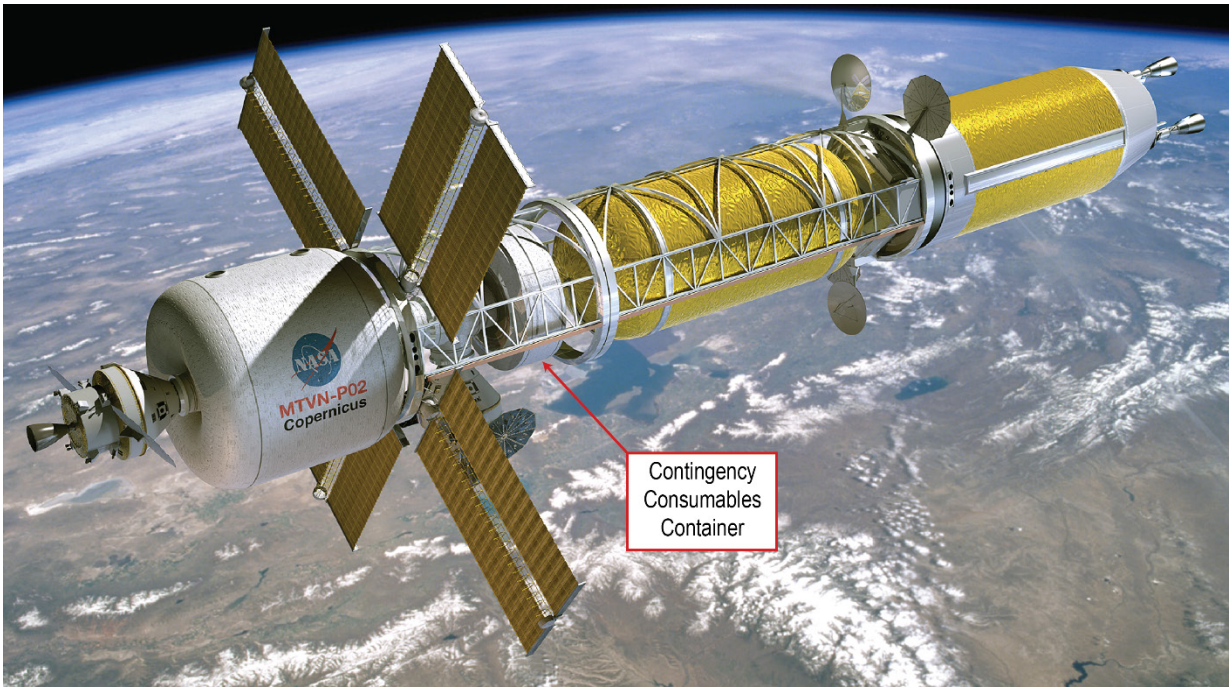

Figure 4.—NTR-Propelled MTV *Copernicus* in LEO – Mars DRA 5.0 (2009)

Today, NASA is contemplating missions to the Moon, cislunar space, near Earth asteroids, Mars and its moons. To determine what role AG should have in future deep space human exploration missions, a 2-day workshop, with international participation, was held (Feb. 19-20, 2014) at the NASA Ames Research Center (ARC). The workshop brought together "… knowledgeable space physiologists, crew surgeons, astronauts, vehicle designers, and mission planners to review, evaluate, and discuss the need for incorporating AG technologies into the vehicle design" (Ref. 15). The workshop White Paper (Ref. 15) provides an excellent overview and summary of past and current activities by engineers and researchers in this area. It also posed key questions that need to be addressed in experiments both on the ground (using short-radius human centrifuges (SRHCs)) and in space (using rodent research on ISS without and with centrifugation up to 1-g for durations ranging from 30 to 180 days). Several different options for implementing AG were also suggested: (1) Intermittent AG involving either spinning an individual in a SRHC inside the spacecraft or spinning a portion of the spacecraft; or (2) Continuous AG involving rotation of the entire spacecraft during transits out to Mars and back (Refs. 8, 9, and 16). It is option 2 that is the focus of this paper.

Covered are the following topics. First, the biomedical effects of prolonged spaceflight in a 0-g are reviewed, then the potential benefits, design parameters and human factors issues to be considered in AG spacecraft design are discussed. Next, the operational principles and engine performance characteristics for the straight NTR (using Rover/NERVA composite fuel) and follow-on BNTR (using ceramic metal cermet fuel) engines considered in this paper are discussed. Mission and transportation system ground rules and assumptions are provided next followed by a brief overview of the DRA 5.0 mission. Results are then presented for three different AG/MTV design options: (1) the single TransHab *Copernicus-B* configuration using BNTP for propulsion and spacecraft electrical power, (2) a stretch version of *Copernicus-B* called *Discovery*, and (3) a twin habitat configuration, named the *A. C. Clarke*, using conventional NTP and PVAs for auxiliary power. The results include key vehicle features and operational characteristics. The impact of the SLS-1B and HLV's estimated lift capability and payload volume on vehicle design is also examined. The paper ends with a summary of our findings and some concluding remarks.

2.0 AG Vehicles: Advantages, Design Parameters, and Human Factor

More than 50 years of human spaceflight have provided a wealth of knowledge on the physiological effects of 0-g and long-term exposure to it. The most significant adverse effects are loss of muscle mass (e.g., back and leg muscles) and the progressive loss of skeletal bone mass (~1.5 percent per month) particularly from the lower vertebrae, hip and femur (Ref. 3). Another significant effect is fluid redistribution to the upper body that may be responsible for in-flight and post-flight changes in vision and eye anatomy, including degraded distant and near vision, swelling of the back of the eye, and a flattening of the globe of the eye. This relatively recent health concern is referred to as visual impairment due to increased intracranial pressure or VIIP (Ref. 4).

Fluid redistribution to the upper body also results in bulging neck veins, puffing of the face and sinus, and nasal congestion that can last throughout the entire mission. In 0-g, astronauts can also lose ~20 percent of their blood volume and with less blood to pump, the heart muscles begin to atrophy, blood pressure drops and insufficient oxygen is sent to the brain leading to fainting and dizziness. Other significant effects include a decreased production of red blood cells and plasma (space anemia), balance disorders and a weakening of the immune system.

Despite a vigorous and time-consuming, daily exercise regimen in orbit, use of lower body negative pressure suits, and drugs on their long duration Mir flights, Russian cosmonauts returning to Earth were unable to walk normally for several days, and also exhibited orthostatic intolerance and musculoskeletal

deterioration requiring lengthy professional rehabilitation for recovery. Similar symptoms were reported by U.S. astronauts after ~4 to 6 months aboard the Mir station. These findings pose an interesting question, "Will future astronauts be able to travel 6 months to Mars in 0-g, land on its surface, don an ~115 lb spacesuit and then be physically and visually fit to walk about its rock-strewn surface doing productive exploration?"

2.1 Advantages of AG Spacecraft

In view of the apparent inadequacy of current in-flight, 0-g countermeasures, an AG environment produced via spacecraft rotation may well provide the solution to ensuring a healthy crew both out to Mars and back. By adjusting the AG environment of the MTV to 1-g for most of the outbound transit time, crew fitness can be maintained at a high level. Approximately a month before Mars encounter, final course adjustments can be made and the AG environment reduced to that of Mars (~3.7 m/s^2 or ~0.38-g) allowing the crew to adjust to and train for operations on the Martian surface. On the return trip, the AG level would start off at 0.38-g but increase by ~0.124-g per month over the next 4 months, thereby providing the crew with a 1-g environment during the final month of the voyage. Also, because the spinning spacecraft would provide a nearly continuous AG environment, concerns about crew compliance with lengthy and tedious 0-g exercise protocols would be eliminated.

Additional secondary benefits (Ref. 8) of AG include the establishment of a well-defined vertical and horizontal reference frame. Trash and particulates eventually settle to or intercept a floor or wall rather than floating about the habitat areas thereby reducing the potential risk of microbiological and/or toxicological contamination of crew members. Conventional toilets, along with normal eating, sleeping, bathing and grooming practices, also become practical, and complex medical procedures, such as surgery can be performed with less difficulty and reduced risk.

2.2 Vehicle Design Parameters

The centrifugal acceleration (a_c) produced by a rotating spacecraft depends on its radius of rotation (r) and angular velocity (ω), and is given by

$$a_c\,(\mathrm{m/s^2}) = [\omega\,(\mathrm{rad/s})]^2 \times r\,(\mathrm{m}). \tag{1}$$

Expressing the angular velocity in revolutions per minute [ω (rad/s) = ω (rpm) × ($2\pi/60$)], Equation (1) can be rewritten as follows:

$$a_c\,(\mathrm{m/s^2}) = 1.097\times10^{-2}\,[\omega\,(\mathrm{rpm})]^2 \times r\,(\mathrm{m}). \tag{2}$$

To provide rotational spin to the spacecraft, clusters of reaction control system (RCS) thrusters are used. On the *Copernicus-B*, RCS thrusters are located at the forward end of the vehicle just behind the TransHab module and at aft end just in front of the LH_2 propellant tank on the core propulsion stage. On the *A. C. Clarke*, RCS thrusters are also located on each of the twin habitat modules. When the thrusters are fired in opposite directions, a torque (τ) is applied to the spacecraft causing it to spin about its CM, creating the centrifugal acceleration and AG environment experienced by the crew. The applied torque is related to the RCS thrust (F), specific impulse (I_{sp}) and propellant flow rate (dm_p/dt) by the following:

$$\tau\,(\mathrm{N\text{-}m}) = F\,(\mathrm{N}) \times L\,(\mathrm{m}) = [dm_p/dt\,(\mathrm{kg/s}) \times g \times I_{sp}\,(\mathrm{s})] \times L\,(\mathrm{m}), \tag{3}$$

where g is Earth's gravitational acceleration (~9.807 m/s^2). The RCS propellant mass (M_p) needed to produce the desired AG level is determined by equating the imparted torque from the thrusters to the spacecraft's polar mass moment of inertia (J) multiplied by the time rate of change in the angular velocity (ω).

$$\tau \text{ (N-m)} = J \text{ (kg-m}^2\text{)} \times d\omega/dt \text{ (s}^{-2}\text{)} \tag{4}$$

By equating Equations (3) and (4), and integrating over time, one obtains the following for the RCS propellant mass:

$$M_p \text{ (kg)} = J \text{ (kg-m}^2\text{)} \times \omega \text{ (s}^{-1}\text{)} / [g \times I_{sp} \text{ (s)} \times L \text{ (m)}]. \tag{5}$$

The polar moment of inertia used in Equations (4) and (5) is a mass property that measures the resistance of a body to a change in angular momentum assuming the amount of propellant that spins the spacecraft is small relative to the overall mass. Polar inertia is determined knowing the mass and centroid of all the components of the craft and summing the total. Items that are difficult to define, such as wiring and plumbing, are smeared throughout the spacecraft. Liquid propellant is assumed to rotate with the spacecraft, owing to the internal components inside a tank, such as the liquid acquisition device, structural ribbing, etc. The sizing code then collects all the major components and sums them to get an overall approximate aggregate for J.

2.3 Human Factors Issues

In designing an AG spacecraft, a number of important human factors (Refs. 8, 11, and 17) must be taken into account in selecting the rotation radius, angular velocity, and g-levels. These factors include the gravity gradient effect, Coriolis forces and cross-coupled acceleration effects. These human factor effects also come into play when considering the orientation of the habitat module or modules (shown in Figure 5) relative to the spin axis of the vehicle. Orientation options include: (1) Radial (used in Concept 3, the *von Braun* and *Copernicus-B*); (2) Tangential (used in Concepts 1, 2, 6 and the *A. C. Clarke* Dumbbell B configuration); and (3) Axial (used in Concepts 4, 5, and a variant of the *A. C. Clarke* referred to as the Dumbbell A configuration). The radial habitat module is by definition a multi-level vertical design. Because the centrifugal acceleration varies directly with the radial distance from the center of rotation, a vertical gravity gradient will exist between the different levels of the hab module(s) and even along the human body itself. Crewmembers climbing up a radial-oriented ladder toward the vehicle's center of rotation would lose weight with each step. Awkward materials handling problems and uneven g-loadings on the body are also possible but are not expected to be significant in AG vehicles with reasonable rotation radii.

Tangential Coriolis forces will also expose the crew to pseudo weight changes depending on their direction of motion with respect to the spin axis of the vehicle. While no Coriolis force occurs when walking parallel to the spin axis, astronauts will feel heavier when moving in the direction of vehicle rotation and lighter when walking in the reverse direction. Transverse Coriolis forces will be experienced by astronauts moving vertically between habitat levels. When climbing up toward the vehicle's center of rotation, the astronauts will be pushed sideways in the direction of spacecraft spin. A sideways push away from the spin direction will be felt when climbing down the ladder (refer to Figure 6).

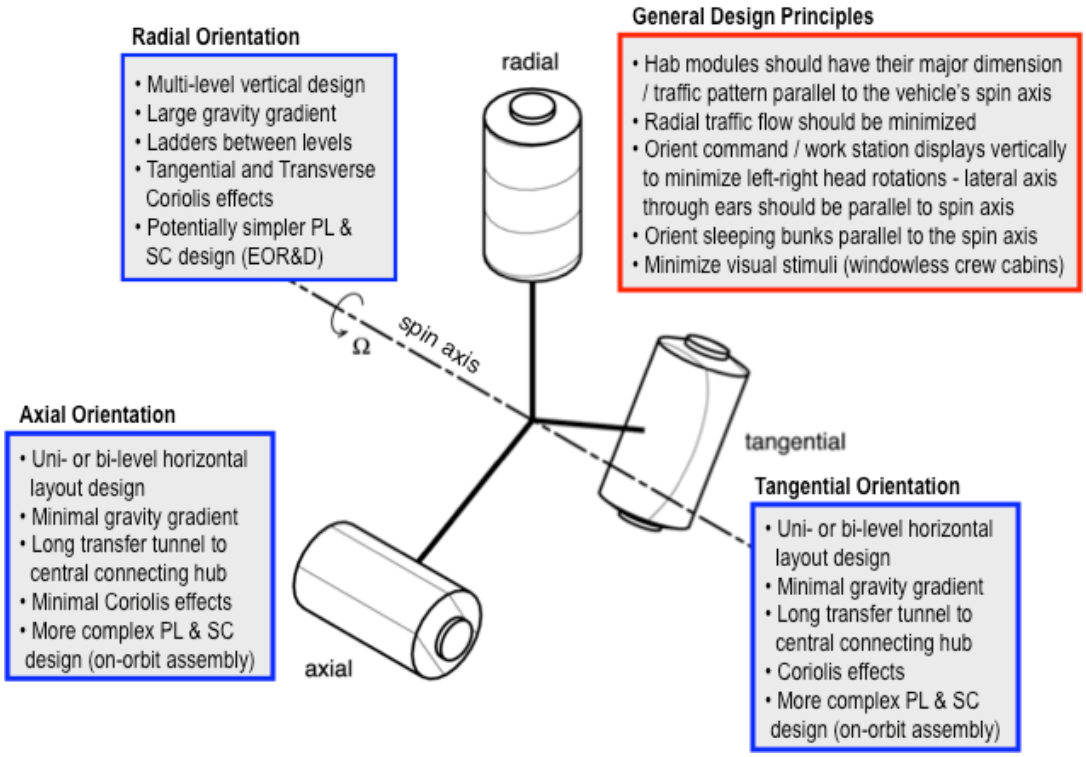

Figure 5.—Options for Habitat Module Orientation and Associated Human Factors

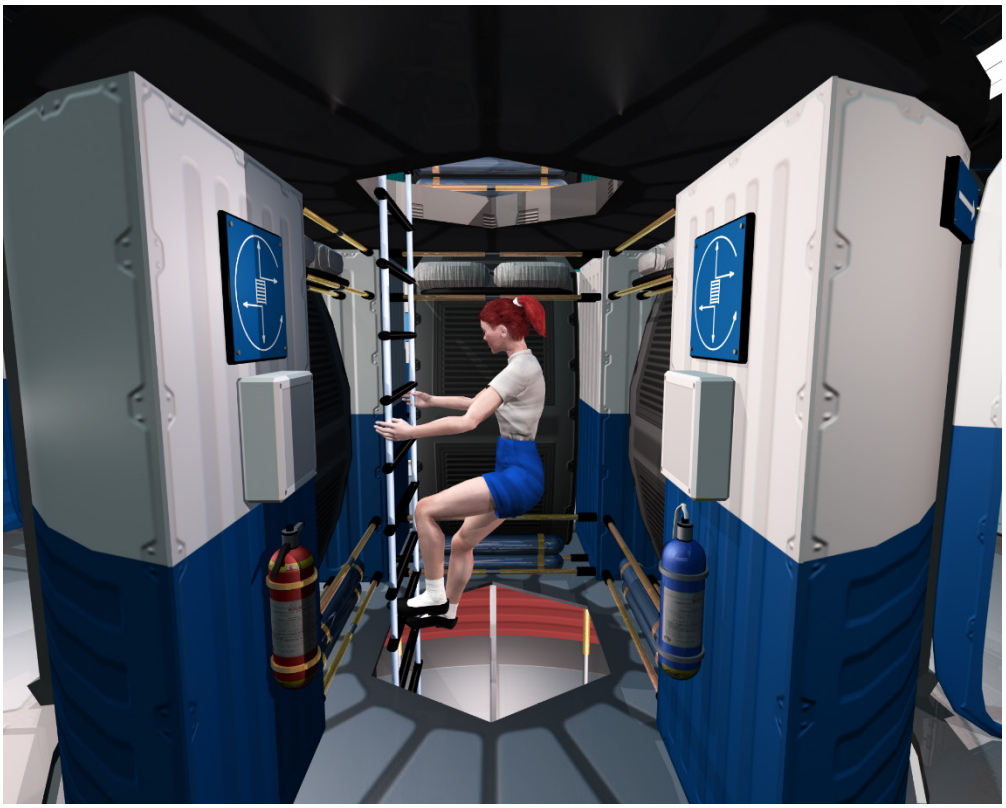

Figure 6.—Posted Visual Cues Show Direction of Transverse Coriolis Forces When Climbing Between Levels

Lastly, cross-coupled angular acceleration effects will be experienced by astronauts early on due to head movement in the directions transverse to the axis of rotation and the primary direction of spacecraft flight. With time and use of distinctive interior color schemes or wall-mounted designations to help identify spin direction (depicted in Figure 6), astronauts should be able to compensate for and acclimate to these AG effects. General design principles for habitats onboard rotating AG spacecraft were provided by Loret (Ref. 17) and are summarized in Figure 5.

Despite the lack of current experimental data (Refs. 10 and 15) needed to establish accepted g-threshold requirements and other operational characteristics (e.g., rotation radius and ω), previous experts (Refs. 18, 19, and 20) in this area used existing physiological and/or human factors data coupled with reasonable assumptions to identify representative operational regions for AG vehicles. Stone (Ref. 18) and Thompson (Ref. 19) recommended a rotation radius $\geq$ 14.6 m and a spin rate $\leq$ 6 rpm, while Shipov (Ref. 20) thought that the minimum radius should be ~20 m.

During the 1960s, researchers (Refs. 21 and 22) at the Naval Medical Research Laboratory in Pensacola, Florida, used their Slow Rotating Room (SRR) to study the acute rotation effects phenomena at rates as high as 10 rpm. Their results indicated that a judicious restriction of head motions and progressive adaptation through stepwise increases in spin rate (1 rpm every 2 days during 16 days of rotation) allowed most human subjects to adjust quickly to avoid the adverse physical symptoms of higher rotation rates. "Later studies have expanded on the experience from that time and demonstrated that complete adaptation to rotation rates as high as 10 rpm can be achieved within minutes if repeated voluntary movements are made. Such movements were avoided in the early Pensacola studies" (Ref. 15). The recent AG workshop White Paper suggested expanding upon the SRR experiments by refurbishing and using the two-room, 52-ft diameter centrifuge at ARC (Ref. 15) to help develop requirements for future rotating vehicles. It also recommended a coordinated global effort to provide data and answers to key questions by 2022. This would allow sufficient time to incorporate AG features into vehicle designs for use on long duration, deep space missions in the late 2020s to early 2030s timeframe should they be needed.

3.0 NTR / BNTR System Descriptions and Performance Characteristics

The NTR uses a compact fission reactor core containing 93 percent enriched uranium (U)-235 fuel to generate 100s of megawatts of thermal power (MW_t) required to heat the LH_2 propellant to high exhaust temperatures for rocket thrust. In an expander cycle Rover/NERVA-type engine (Figure 7), high pressure LH_2 flowing from either a single or twin turbopump assembly (TPA) is split into two paths with the first cooling the engine's nozzle, pressure vessel, neutron reflector, and control drums, and the second path cooling the engine's tie-tube assemblies. The flows are then merged and the heated H_2 gas is used to drive the TPAs. The hydrogen turbine exhaust is then routed back into the reactor pressure vessel and through the internal radiation shield and core support structure before entering the coolant channels in the reactor core's fuel elements (FEs). Here it absorbs energy produced from the fission of U-235 atoms, is superheated to high exhaust temperatures (T_{ex} ~2550 to 2950 K depending on fuel type and U loading), then expanded out a high area ratio nozzle (~300:1) for thrust generation.

Controlling the NTR during its various operational phases (startup, full thrust and shutdown) is accomplished by matching the TPA-supplied LH_2 flow to the reactor power level. Twelve rotating boron carbide (B_4C) control drums, located in the beryllium (Be) reflector region surrounding the reactor core, regulate the neutron population and reactor power level over the NTR's operational lifetime. The internal neutron and gamma radiation shield, located within the engine's pressure vessel, contains its own interior coolant channels. It is placed between the reactor core and key engine components to prevent excessive radiation heating and material damage.

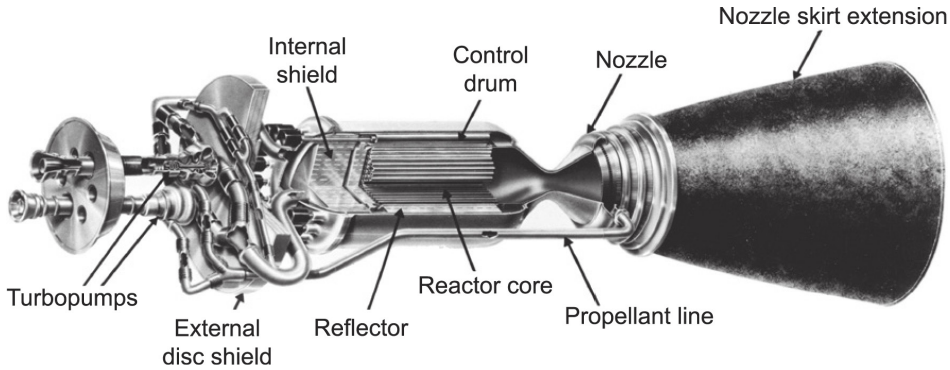

Figure 7.—Schematic of Expander Cycle NTR Engine With Dual LH_2 Turbopumps

The FEs tested in the Rover / NERVA program (Ref. 13) consisted of a graphite matrix material that contained the U-235 fuel in the form of either coated particles of uranium carbide (UC_2) or as a dispersion of uranium and zirconium carbide (UC-ZrC) referred to as composite fuel. Each FE (see Figure 8) had a hexagonal cross section (~0.75 in. across the flats) and 19 axial coolant channels that were coated with niobium carbide (NbC) initially, then with zirconium carbide (ZrC) using a chemical vapor deposition (CVD) process. This protective coating, applied to the exterior FE surfaces as well, helped reduce hydrogen erosion of the graphite. Individual elements were 1.32 m (52 in.) in length and produced ~1 MW_t.

This basic FE shape and length was introduced in the KIWI-B4E reactor and became the standard used in the 75 klb_f Phoebus-1B, 250 klb_f Phoebus-2A, 25 klb_f Pewee and the 55 klb_f NERVA NRX series of engines (Ref. 13). The Rover program's Pewee engine (Ref. 13) was designed and built to evaluate higher temperature, longer life fuel elements and improved coatings. It set several performance records including the highest average fuel element exit gas temperature of ~2550 K, and the highest peak fuel temperature ~2750 K. Other performance records included average and peak power densities in the reactor core of ~2340 and ~5200 MW_t/m^3, respectively. A new CVD coating of ZrC was also introduced in Pewee that showed performance superior to the NbC coating used in previous reactor tests.

In addition to FEs, the engine reactor cores also included tie tube (TT) elements of the same hexagonal shape that provided structural support for the FEs. A coaxial coolant tube of Inconel inside each TT supplied a source of heated hydrogen for turbine drive power and a sleeve of zirconium hydride (ZrH) moderator material could also be incorporated in the TTs to help raise neutron reactivity (shown in Figure 8). In the larger size engines tested during the Rover / NERVA programs, a sparse FE-TT arrangement was used with each FE having two adjacent TTs and four adjacent FEs comprising its six surrounding elements (Ref. 23). In this sparse pattern, the FE to TT ratio is ~3 to 1.

In the Small Nuclear Rocket Engine (SNRE) design developed by Los Alamos National Laboratory near the end of Rover / NERVA (Ref. 24), shorter (0.89 m/35 in.) FEs were used so additional TTs were included in the reactor to increase core reactivity. With the SNRE FE-TT pattern each FE has three adjacent TTs and three adjacent FEs surrounding it (shown in Figure 8) and the FE to TT ratio is ~2 to 1. An important feature common to both the sparse and SNRE FE-TT patterns is that each TT provides mechanical support for six adjacent fuel elements.

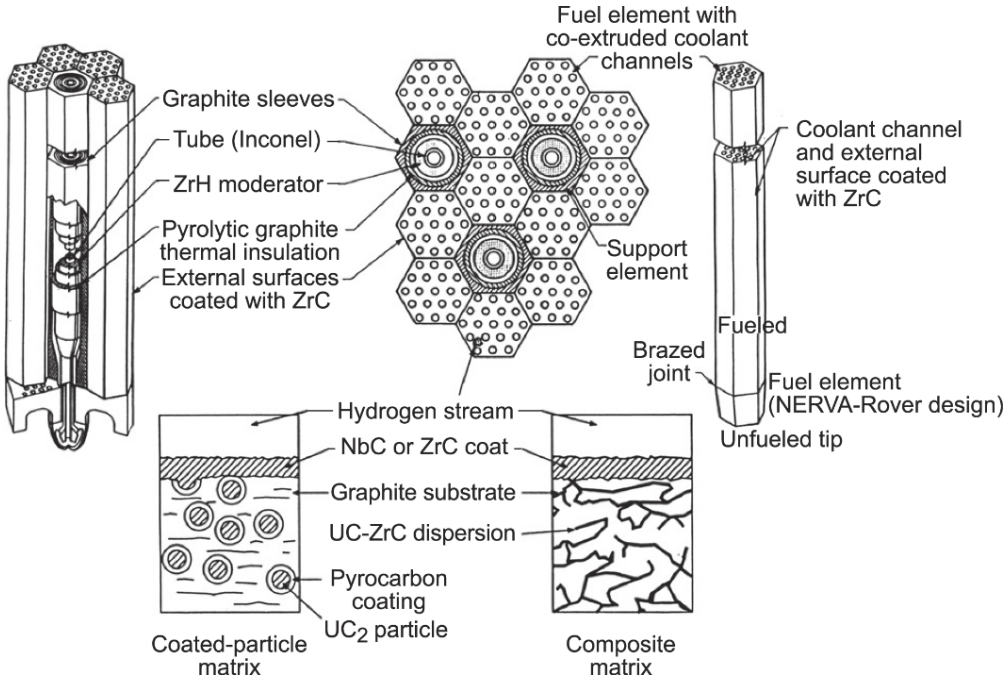

Figure 8.—Coated Particle and Composite SNRE Fuel Element and Tie Tube Arrangement

Recent Monte Carlo N-Particle (MCNP) transport modeling of these thermal / epithermal spectrum reactor cores by Schnitzler et al., (Refs. 23, 25, and 26) has shown that the SNRE design can be scaled down to even lower thrust levels (~5.3 to 7.4 klb_f) or up to the 25 klb_f Pewee-class engine used in Mars DRA 5.0. For low thrust engines, short length elements (~0.89 m) and a dense FE – TT pattern are used consisting of parallel rows of FEs and TTs. Each FE has four adjacent TTs and two adjacent FEs surrounding it and the FE to TT ratio is ~1 to 1. By using the SNRE FE – TT pattern and increasing the FE length from 0.89 m to 1.32 m (the same length used in the Rover program's Pewee engine), the U-235 fuel loading in the core can be lowered from ~0.60 to 0.25 grams/cm^3 allowing the FEs to operate at higher peak fuel temperatures (T_{peak}) while still staying safely below the melt temperature for composite fuel of ~3050 K. It also allows higher hydrogen exhaust / higher chamber inlet temperatures thereby increasing the engine's I_{sp} capability. Higher I_{sp} operation can help stretch the available LH_2 propellant loading to meet mission requirements, or in the case of an emergency to allow a safe return of the crew.

The reference NTR engine used in DRA 5.0 and this paper is a 25 klb_f Pewee-class engine based on the axial-growth version of the SNRE. It utilizes an expander cycle and has the following nominal performance parameters: T_{ex} ~2790 K, chamber pressure ~1000 psia, nozzle area ratio (NAR) ~300:1, and I_{sp} ~906 s. The LH_2 flow rate is ~12.5 kg/s and the engine thrust-to-weight ratio is ~3.50. The overall engine length is ~7.01 m, which includes an ~2.16 m long, retractable radiation-cooled nozzle skirt extension. The nozzle exit diameter is ~1.87 m. The higher chamber pressure helps to maintain reasonable nozzle dimensions at the assumed NAR. The engine's reactor core contains 564 FEs and 241 TTs that are 1.32 m long like those used in Pewee. The core power level and fuel matrix power density are ~560 MW_t and ~3.44 MW_t / liter, respectively. The U-235 fuel loading used in the reactor FEs is ~0.25 grams / cm^3 and the inventory of 93 percent enriched U-235 in the core is just under 37 kg. At this fuel loading the engine is able to operate at a T_{peak} of ~2860 K providing a temperature margin to fuel melt of ~190 K. During enhanced operation T_{peak} is raised to ~3010 K (a margin-to-melt temperature of ~40 K) and T_{ex} to ~2940 K resulting in an ~35 s increase in I_{sp} to ~940 s, if needed.

High temperature UC-ZrC in graphite composite fuel with ZrC coating is the primary fuel form used in the Pewee-class engines. Composite FEs were first tested in the Nuclear Furnace element test reactor (Ref. 13) and withstood peak power densities of ~4500 to 5000 MW_t/m^3. They also demonstrated better corrosion resistance than the standard coated particle graphite matrix fuel element used in the previous Rover/NERVA reactor tests. Composite fuel's improved corrosion resistance is attributed to its higher coefficient of thermal expansion that more closely matches that of the protective ZrC coating, thereby helping to reduce coating cracking. Electrical-heated composite fuel elements were also tested by Westinghouse in hot hydrogen at 2700 K for ~600 min—equivalent to ten 1-hr cycles. At the end of Rover / NERVA program, composite fuel performance projections (Ref. 27) were estimated at ~2 to 6 hr at full power for hydrogen exhaust temperatures of ~2500 to 2800 K.

As mentioned in the Introduction, the motivation for selecting NTP as the propulsion system of choice for Mars is simple—it is a proven technology with a specific impulse that is twice that of today's best chemical rockets. During the Rover / NERVA programs (1955 to 1972), a technology readiness level (TRL) ~5 to 6 was achieved (Ref. 13). Twenty rocket reactors were designed, built and ground tested in integrated reactor / engine tests that demonstrated: (1) a wide range of thrust levels (~25, 50, 75 and 250 klb_f); (2) high temperature carbide-based nuclear fuels that provided hydrogen exhaust temperatures up to 2550 K (*achieved in Pewee*); (3) sustained engine operation (*over 62 min for a single burn achieved in the NRX-A6*); as well as (4) accumulated lifetime at full-power; and (5) restart capability (*>2 hr with 28 startup and shutdown cycles achieved in the NRX-XE experimental engine*)—all the requirements needed for a human Mars mission. Just as important, NTP requires no large scale-ups in size or performance like that required with other advanced propulsion options. Three Pewee-class engines are sufficient.

3.1 Bimodal NTR Option

Besides providing high thrust at high I_{sp}, the NTR also represents a rich energy source because it contains substantially more U-235 fuel in its reactor core than is consumed during the primary propulsion maneuvers performed in a typical Mars mission. By reconfiguring the NTR for bimodal operation (Ref. 28) (both thrust and power production), the BNTR can generate 10s of kilowatts of electrical power for crew life support, high data-rate communications, and zero-boiloff (ZBO) LH_2 propellant storage using an active refrigeration system. Like the conventional NTR, the BNTR engine's reactor produces 100s of MW_t during the high thrust propulsion phase. During the mission coast / power generation phase, the BNTR's reactor continues to operate but in an idle mode at greatly reduced power levels (~125 kW_t to produce ~25 kW_e). Energy generated in the reactor fuel assemblies is removed using a secondary closed coolant loop that carries a He-Xe gas mixture to a Bratyon cycle power conversion system.

The BNTR design selected and used in this study is the trimodal NTR concept engine, called TRITON (Ref. 29). It is based on collaborative work between Pratt and Whitney, Aerojet (now Aerojet Rocketdyne), GRC and RENMAR. The TRITON engine uses ceramic-metallic or cermet fuel elements consisting of uranium dioxide (UO_2) in a tungsten (W) metal matrix. This fast spectrum reactor fuel type was developed in the ANL and GE-710 nuclear rocket programs (Refs. 30 and 31) as a backup to the Rover/NERVA fuel. To generate electricity, each UO_2-W fuel element in TRITON's reactor core has integrated into it a closed loop, coaxial energy transport duct (ETD) that carries the He-Xe coolant. The heated gas (at ~1300 K) is then routed to a 25 kW_e-class BRU using a turbine-alternator-compressor assembly that generates electricity at ~20 percent conversion efficiency. Waste heat is rejected to space using a conical pumped-loop radiator mounted to the exterior of the propulsion stage thrust structure (shown in Figure 3). The radiator also helps remove low level decay heat power from the engines following high thrust operation.

TRITON's third feature includes an oxygen afterburner nozzle that uses an oxygen-rich gas generator (GG) to provide gasified oxygen downstream of the nozzle throat at a NAR of ~40:1. Here it mixes with reactor-heated H_2 and undergoes supersonic combustion adding both mass and chemical energy to the rocket exhaust. By controlling the oxygen-to-hydrogen mixture ratio, TRITON can operate over a wide range of thrust and I_{sp} levels while the reactor core power level remains relatively constant. A simplified schematic and key features of the TRITON engine are shown in Figure 9 and Figure 10.

The 25 klb_f-class TRITON engines considered in this study use an expander cycle and have the following performance parameters: T_{ex} ~2700 K, chamber pressure ~1000 psia, NAR ~300:1, I_{sp} ~911 s and LH_2 flow rate of ~12.45 kg/s. The engine thrust-to-weight (F/W_{eng}) ratio is ~5.5 although ongoing studies (Ref. 32) indicate that a value of ~4.0 may be more appropriate. The overall engine length varies from ~6.25 to 6.5 m (depending on FE length), which includes the ~1.93 m long, retractable radiation-cooled nozzle skirt extension. The nozzle exit diameter is ~1.75 m.

The engine's reactor core contains ~199 UO_2-W fuel elements with a fuel composition, by volume, of 60% UO_2, 34% W, and 6% gadolinium oxide (Gd_2O_3)—an oxygen stabilizer. The FE coolant channels and exterior surfaces are also clad with a tungsten rhenium (W-Re) alloy. Each FE has a hexagonal cross section (~1.70 in. across the flats) and 48 axial flow, hydrogen coolant channels. The length of the fuel elements can vary from ~61 to 86.4 cm (24 to 34 in.) (Ref. 32). The core power level and fuel matrix power density are ~530 MW_t and ~3.52 MW_t/liter, respectively.

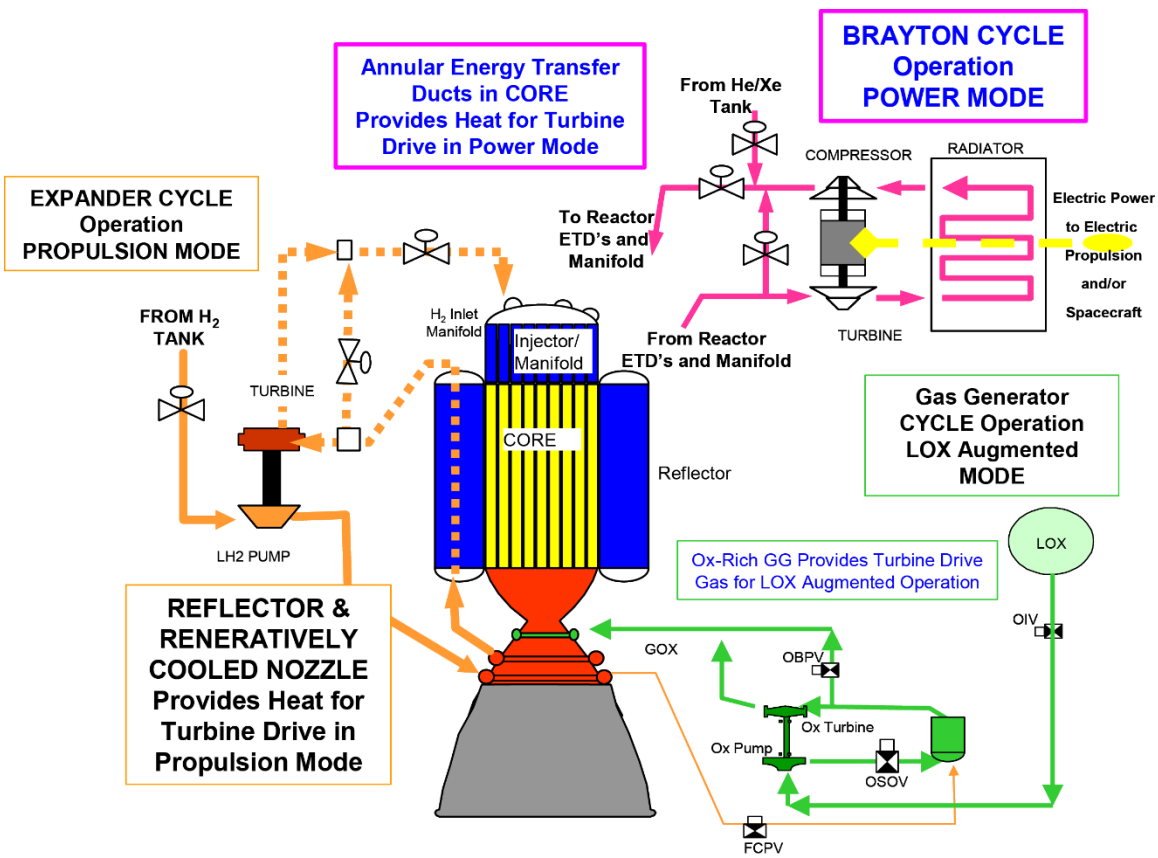

Figure 9.—TRITON Schematic Showing Brayton Cycle and O_2 Afterburner GG Flowpaths (Ref. 29)

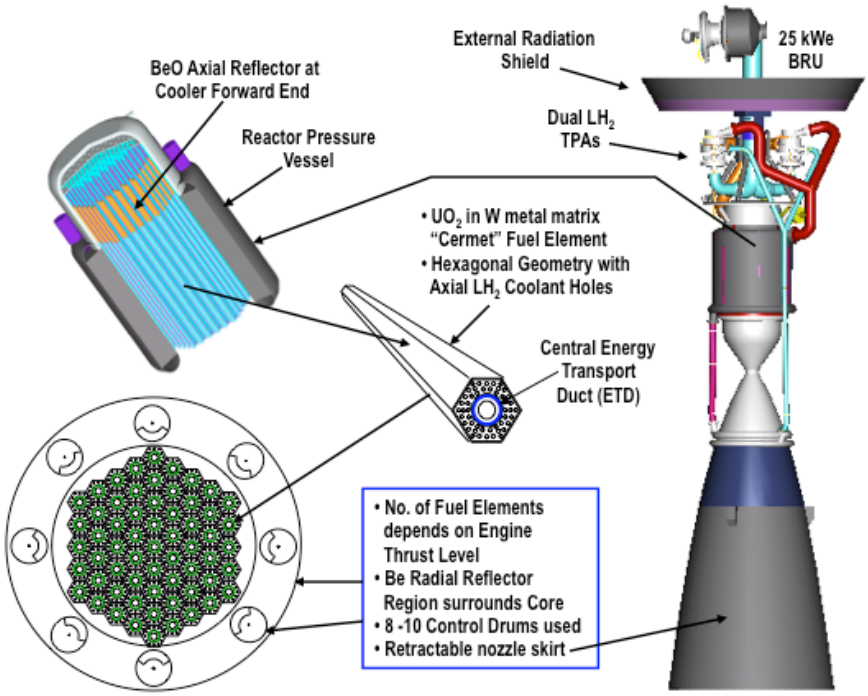

Figure 10.—Some Key Features of the TRITON BNTR Engine (Ref. 29)

For a fast spectrum system, the inventory of highly enriched (93%) U-235 (HEU) mass in the core is significantly higher. For the 25 klb_f thermal spectrum Pewee-class engine discussed above, the amount of HEU is ~37 kg. By contrast, the same thrust class engine using a variant of the heritage GE-710 fuel element design requires ~225 kg of HEU (Ref. 32). An order of magnitude higher HEU inventory over that found in the Pewee-class engine is expected in the TRITON engine due in part to the additional internal hardware (ETD) in each FE used for electrical power generation. The fuel matrix power density used in the TRITON engine (~3.52 MW_t/liter) is also the lowest of the heritage cermet-fueled engine designs examined by Schnitzler (Ref. 32) which range from ~5.40 MW_t/liter for the ANL-200 (Ref. 30) to ~13.5 MW_t/liter for the GE-710 (Ref. 31). If integrated multi-physics (thermal, fluid, and structural) analyses (Ref. 33) confirms that higher fuel matrix power density operation in the TRITON design is possible, it is expected that core masses and fissile inventories could be reduced.

Other key features of the TRITON engine include a radial Be reflector and an axial beryllium oxide (BeO) reflector located at the top of the reactor core. Reactivity control is provided by cylindrical control drums located in the radial reflector region. These rotating drums contain a neutron absorber material, like B_4C, located over a portion of the control drum facing the reactor core as shown in Figure 10.

4.0 Mission and Transportation System Ground Rules and Assumptions

Specific mission and NTR transportation system ground rules and assumptions used in this paper are summarized in Table I and Table II, respectively. Table I provides information about the crewed mission scenario, assumed parking orbits at Earth and Mars, along with the ΔV budget for the round trip fast conjunction, crewed mission used in DRA 5.0. In addition to the large ΔV requirements shown for the primary propulsion maneuvers (TMI, MOC and trans-Earth injection (TEI)), smaller ΔV maneuvers are also needed for rendezvous and docking (R&D) of MTV components during the LEO assembly phase, for spacecraft attitude control during in-space transit, Mars orbital operations, and for vehicle rotation spin-up/spin-down maneuvers.

TABLE I.—MISSION AND PAYLOAD GROUND RULES AND ASSUMPTIONS

Mars DRA 5.0 Mission Profile	• Split mission; cargo pre-deployed to Mars before crew leaves Earth • Cargo missions use one-way minimum energy trajectory • Round trip crewed missions use fast conjunction trajectories • Landing mission with long surface stay (~540 days) • Direct return uses *Orion* capsule for crew recovery at mission end
Mission depart from LEO; capture into and depart from a 24-hr elliptical Mars orbit (EMO)	• LEO: 407 km circular • 24 hr EMO: 250 km by 33,793 km
All propulsive crewed mission ΔV budgets	• Earth departure C_3 ~18.40 km^2/s^2, ΔV_{TMI} ~3.992 km/s, arrival V_{inf} ~4.176 km/s, ΔV_{MOC} ~1.771 km/s • Mars departure C_3 ~14.80 km^2/s^2, ΔV_{TEI} ~1.562 km/s • *Note*: Gravity losses added to above ideal ΔV
Additional ΔV requirements: Advanced Material Bipropellant Rocket (AMBR) RCS thrusters used to perform nonprimary propulsion maneuvers; also to initiate and stop vehicle rotation during transit out to Mars and back	• LEO R&D between orbital elements: 15 to 100 m/s • Coast attitude control and midcourse corrections: ~15 and ~500 m/s, respectively • Mars orbit maintenance plus R&D: 100 m/s • RCS propellant mass for vehicle spin-up/spin-down determined by Equation (5)
Crewed mission payload masses: Varies with crew size, mission duration, and assumed habitat design; consumables based on a crew consumption rate of ~2.45 kg/person/day; Other possible payload elements include short saddle truss (SST) and transfer tunnel with second docking module (TDM); a central logistics module with twin long transfer tunnels and supports; an exterior contingency consumables container(s) that can be jettisoned prior to the TEI maneuver; and other equipment	• Single TransHab Module: 25.0 t (minus consumables) • SST/TDM/container: 5.08 t/1.76 t/23% of stored food • Twin Stretch ISS Modules: 34.0 t (minus consumables) • Central Logistics Hub: 7.15 t • Twin Transfer Tunnels: 2 x 1.625 t per tunnel + 2.25 t supports • Other Equipment: 8.21 t (on ISS Modules) • Crew (5 to 6) and Suits: 1.0 to 1.2 t • Total consumables: 4.47 to 5.37 t (five to six crew for 1-year); with extra consumables stored in exterior container • *Orion* MPCV: ~13.5 t • Returned samples: 0.25 t (Mars)
Mission abort strategy	• Outbound: Abort to Mars surface • At Mars: Abort to the orbiting AG/MTV which carries contingency consumables onboard and provides AG environment for the crew

For the crewed mission, the outbound payload mass varies with the crew size and mission duration. For long surface stay Mars missions, the MTV carries contingency consumables equivalent to that found on the habitat lander. This allows the MTV to function as an orbital safe haven in the event of a major failure of a key surface system. On the AG/MTV designs using BNTP, these extra consumables are stored in a single large container attached to the rear of the TransHab module via a transfer tunnel enclosed within a SST (like that shown in Figure 4). On the AG/MTV using NTP, two smaller containers are used and are attached to a central logistics and docking hub located at the front of the vehicle. For the nominal surface mission, the contingency consumables are jettisoned prior to the TEI maneuver. Other payload elements include the *Orion* Multi-Purpose Crew Vehicle (MPCV). For Mars DRA 5.0 and in this analysis it is assumed that ~250 kg of samples are returned.

Table II lists the key transportation system ground rules and assumptions. The system characteristics of the NTR and BNTR engines discussed in Section 3.0 are summarized first. The total LH_2 propellant loading for the Mars mission consists of the usable propellant plus performance reserve, post-burn engine cooldown, and tank trapped residuals. For the smaller auxiliary maneuvers, a storable bipropellant RCS system is used. The AG/MTV designs using BNTP have a split RCS with 16 of 32 thrusters and

approximately half of the bipropellant mass located on the rear NTPS and the SST forward adaptor ring just behind the TransHab module. Designs using NTP and extended twin habitat modules have additional RCS thrusters attached to each module.

TABLE II.—NTR/BNTR TRANSPORTATION SYSTEM GROUND RULES AND ASSUMPTIONS

NTR System characteristics	• Engine/fuel type: SNRE-derived/UC-ZrC composite • Thrust level: 25 klb_f (Pewee-class) • Fuel element length: 1.32 m • Exhaust temperature: T_{ex} ~2790 to 2940 K • I_{sp} range: 906 s (2790 K) to 941 s (2940 K)
BNTR System characteristics	• Engine/fuel type: TRITON-derived/UO_2-W cermet • Thrust level: 25 klb_f (TRITON scale-up) • Fuel element length: 0.61 to 0.864 m • Exhaust temperature: T_{ex} ~2700 K • I_{sp}: 911 s
Common NTR/BNTR characteristics	• No. of engines: Three engine cluster on core NTPS • Propellant: LH_2 • Chamber pressure: p_{ch} ~1000 psi • Nozzle area ratio: 300:1
Propellant margins	• Cooldown: 3% of usable LH_2 propellant • Performance reserve: 1% on ΔV • Tank trapped residuals: 2% of total tank capacity
RCS (LEO R&D, settling, Attitude Coast Control, mid-course corrections burns and vehicle spin-up/spin-down)	• Propulsion type: AMBR 200 lb_f thrusters • Propellant: NTO/N_2H_2 • Nominal I_{sp}: 335 s
LH_2 cryogenic tanks and passive Thermal Protection System (TPS)	• Material: Aluminum-lithium (Al-Li) • Tank D: 8.4 to 10 m • Tank L: ~19.7 m (for core NTPS) ~21.5 to 22.2 m (for in-line tanks) ~12.0/21.7 m (for short/long drop tanks) • Geometry: Cylindrical with root 2/2 ellipsoidal domes • Insulation: 1-in. SOFI (~0.78 kg/m^2) + 60 layers of multilayer insulation (MLI) (~0.90 kg/m^2)
Active Cryo-Fluid Management/ZBO LH_2 Propellant System	• Reverse turbo-Brayton ZBO cryocooler system powered by PVAs • ZBO system mass and power requirements driven by core stage size; ~896 kg and ~8.87 kW_e (10.0 m D); ~790 kg and ~7.25 kW_e (8.4 m D);
PVAs and BRUs for primary power generation	• Circular PVA and sized for ~7 kWe at 1 AU; two to three arrays provide power for ZBO cryocoolers on core NTPS and in-line tanks when used, PVA mass is ~248 kg and array area is ~25 m^2; to supply ~1 kW_e in Mars orbit requires ~8 to 10 m^2 of primary array area mounted on habitats and tunnels • Three 25 kW_e BRUs operating at 2/3rd of rated power supply 50 kW_e • Keep alive power supplied by Li-ion battery system
Dry weight contingency (DWC) factors	• 30% on NTR system and composite structures (e.g., saddle and star trusses) • 15% on established propulsion, propellant tanks, spacecraft systems
SLS-1B/HLV launch requirements: • Lift capability to LEO • Payload (PL) fairing diameter	• ~105 to 140 t; NTPS/BNTPS with external crew radiation shields • 10 to 12 m (12 m for 140 t HLV used in seven-launch option)

The LH_2 propellant used during the crewed Mars mission is stored in the same state-of-the-art Al/Li LH_2 propellant tanks being developed for the SLS, the Block 1B upgrade, and Block II HLV that will support future human exploration missions. For this analysis, tank sizing assumes a 30 psi ullage pressure, 5-g axial / 2.5-g lateral launch loads, and a safety factor of 1.5. A 3 percent ullage factor is also assumed. All tanks use a combination foam/MLI system for passive thermal protection. A ZBO reverse turbo-Brayton cryocooler system is used on both the core NTPS and bimodal NTPS (BNTPS) and in-line LH_2 tanks (where required) to eliminate boil-off during LEO assembly and the remainder of the mission. The propellant tank heat load is largest in LEO and sizes the ZBO cryocooler systems. Two ~7 kW_e MegaFlex PVAs, on both the NTPS and in-line tank elements, provide the power needed to run their cryocoolers with margin to spare.

For the AG/MTV designs using NTP, the primary electrical power for the crewed PL and its key subsystems is supplied by PVAs mounted to either the twin habitat modules and their access tunnels, or to the habitat module's support structure (described in more detail in Sec. 8.0). Because of the decreased solar radiation (~486 W/m^2) at Mars, array areas can become quite large (~8 to 10 m^2/kW_e) depending on the crew size and electrical power needs at Mars. For the AG/MTV designs using BNTP, the engines and their BRUs supply the power needs of the vehicle.

Table 2 also provides the assumed DWC factors, along with the SLS-1B / HLV lift and payload fairing size requirements. A 30 percent DWC is used on the NTR system and advanced composite structures (e.g., stage adaptors, trusses) and 15 percent on heritage systems (e.g., Al/Li tanks, RCS, etc.). The crewed MTV's NTPS and payload element drive the SLS-1B / HLV lift capability and fairing size, respectively. For the seven-launch Mars DRA 5.0 option (Ref. 14), the optimum tank diameter (D) and mass for the NTPS was 10 m and ~140 t, respectively. The crewed PL element included the packaged TransHab module with its PVA power system, the SST, consumables container, and a transfer tunnel with secondary docking module (TDM) shown in Figure 4 and Figure 12. The PL envelope's D was ~11 m (the saddle truss outer dimension) and its length (L) was ~24.9 m (~33.8 m if the *Orion* MPCV is included as part of the launched PL element (Ref. 14)), necessitating a large 12 m D fairing. In this study, 8.4 m D propellant tanks are also used which are compatible with a 10 m D fairing. As before, it is the mass of the NTPS and BNTPS that drives the SLS-1B / HLV lift requirements which vary from ~105 to 140 t.

5.0 Mars DRA 5.0: Seven-Launch NTR Mission Overview

The DRA 5.0 Seven-Launch strategy (Ref. 14) for a Mars landing mission is illustrated in Figure 11. It assumes a long surface stay, split cargo / piloted mission approach. Two cargo flights pre-deploy a cargo lander to the surface and a habitat lander into Mars orbit where it remains until the arrival of the crew on the next mission opportunity. The cargo flights utilize one-way minimum energy, long transit time trajectories. Four HLV flights carried out over 90 days (~30 days between launches), deliver the required components for the two cargo vehicles. The first two launches deliver the NTP stages each with three 25 klb_f NTR engines. The next two launches deliver the cargo and habitat lander payload elements which are enclosed within a large triconic-shaped aeroshell that functions as a payload shroud during launch, then as an AB and thermal protection system during Mars AC and subsequent entry, descent and landing (EDL) on Mars. Vehicle assembly involves Earth orbit R&D between the propulsion stages and payload elements with the NTP stages functioning as the active element in the R&D maneuver.

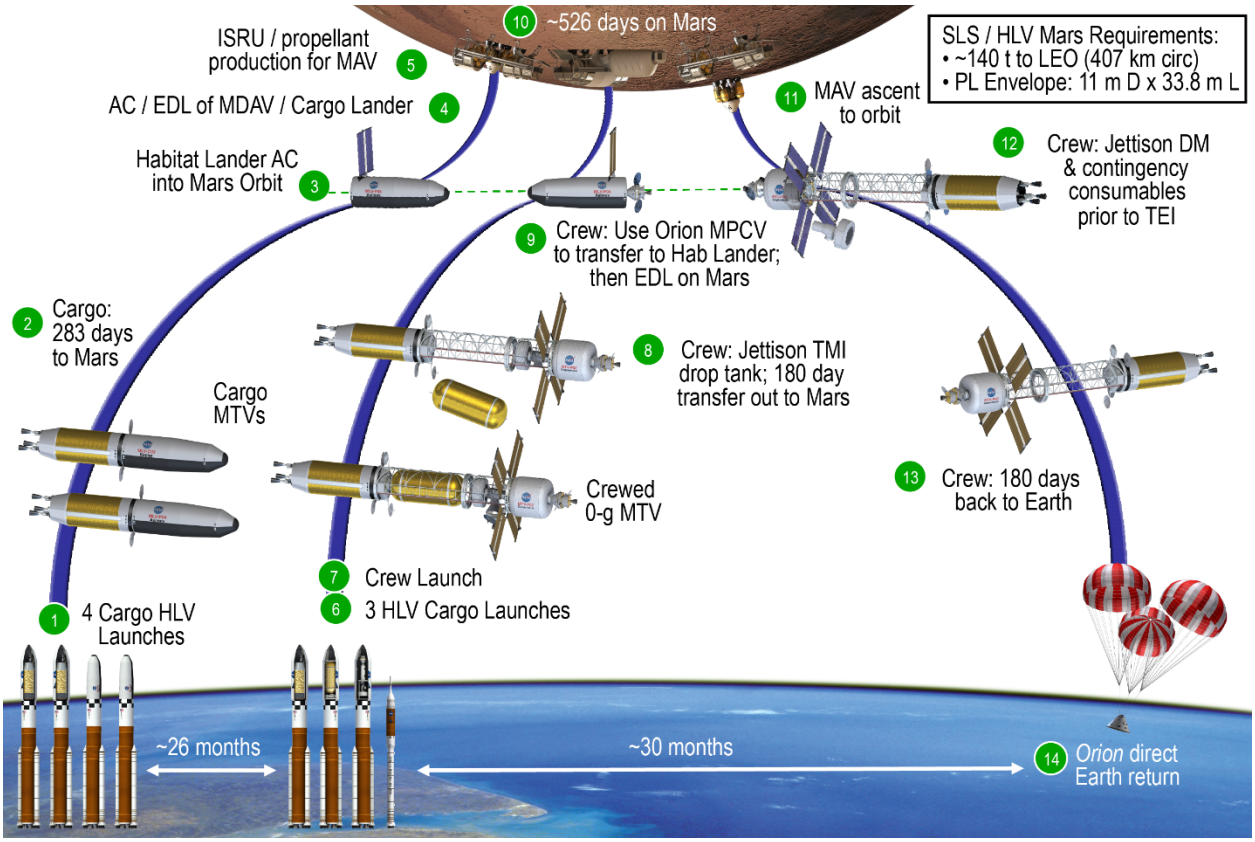

Figure 11.—DRA 5.0 Long-Stay Mars Mission Overview: Seven-Launch NTR Strategy

Once the operational functions of the orbiting habitat and surface cargo landers are verified, and the Mars Ascent Vehicle (MAV) is supplied with in situ resource utilization (ISRU)-produced ascent propellant, the crewed MTV is readied and departs on the next mission opportunity ~26 months later. The crewed 0-g MTV, *Copernicus*, is capable of one-way transit times ranging from ~150 to 220 days depending on the particular opportunity. Like the cargo MTVs, *Copernicus* is assembled in LEO using Earth orbit R&D. It uses the same common NTPS but includes additional external radiation shielding on each engine for crew protection during engine operation. Three HLV launches over 60 days are used to deliver the vehicle's key elements which include: (1) the NTPS; (2) the integrated saddle truss and LH_2 drop tank assembly; and (3) the crewed payload. The payload element includes the TransHab module with its six crew, the *Orion* MPCV for vehicle-to-vehicle transfer and end of mission re-entry, a secondary T-shaped docking module (DM), a contingency consumables container and connecting structure. Four 12.5 kW_e/125 m^2 rectangular PVAs provide ~50 kW_e of electrical power at Mars for crew life-support (~30 kW_e), a ZBO Brayton cryocooler system (~10 kW_e), and high data-rate communications (~10 kW_e) with Earth.

When assembly is completed, the Mars crew is delivered to LEO using either the MPCV and SLS or a commercial crew launch vehicle and docks with *Copernicus* on its underside using the secondary DM that connects the TransHab crew module and contingency consumables container (shown in Figure 4 and Figure 12). Following the TMI maneuver, the drained LH_2 drop tank, attached to the saddle truss, is jettisoned and *Copernicus* coasts to Mars under 0-g conditions with its four PVAs tracking the Sun. Attitude control and mid-course correction maneuvers are provided by *Copernicus*' split RCS that uses 200 lb_f storable bipropellant AMBR thrusters located on the rear NTPS and the SST forward adaptor ring just behind the TransHab module. After a 180-day transit out to Mars, *Copernicus* performs the MOC burn then rendezvous with the orbiting Hab lander using engine cool-down thrust and the vehicle's RCS. After a week in Mars orbit

checking out the landing site and preparing *Copernicus* for autonomous operations, the crew transfers over to the lander in the MPCV which subsequently returns and docks to the TransHab autonomously. The crew then initiates EDL near the cargo lander and begins the surface exploration phase of the mission. After ~526 days on the surface, the crew lifts off using the MAV and returns to *Copernicus* using its secondary TDM (shown in Figure 12). Following the transfer of the crew and samples, the MAV is jettisoned. The crew then begins a weeklong checkout and verification of all MTV systems, jettisons the TDM and contingency consumables and performs the TEI burn to begin the journey back to Earth. After a 180-day return trip, the crew enters the MPCV, separates from the MTV and re-enters Earth's atmosphere while *Copernicus* flies by Earth at a sufficiently high altitude and is disposed of into heliocentric space. Although *Copernicus* was operated in an expendable mission mode in DRA 5.0 to reduce total IMLEO and number of HLV launches, it can readily be modified to operate in a reuse mode by providing the vehicle with additional propellant capacity as discussed elsewhere (Ref. 34).

The *Copernicus* crewed MTV had an overall length of ~93.7 m and an IMLEO of ~336.5 t which included the following: (1) the NTPS (~138.1 t); (2) the saddle truss and LH_2 drop tank (~133.4 t); and (3) the crew payload section (~65 t). Additional size and mass details on the *Copernicus* MTV are found elsewhere (Refs. 34 and 35).

The performance requirements on operating time and restart for *Copernicus*' three 25 klb_f NTR engines were also quite reasonable. For the round trip mission, there were four primary burns (three restarts) that used ~178.4 t of LH_2 propellant. With ~75 klb_f of total thrust and a I_{sp} of ~906 s, the total engine burn time for the mission was ~79.2 min (~55 min for the 2-perigee burn TMI maneuver, ~14.5 min for MOC, and ~9.7 min for TEI), well under the ~2 hr accumulated engine burn time and 27 restarts demonstrated by the NERVA eXperimental Engine—the NRX-XE (Ref. 13).

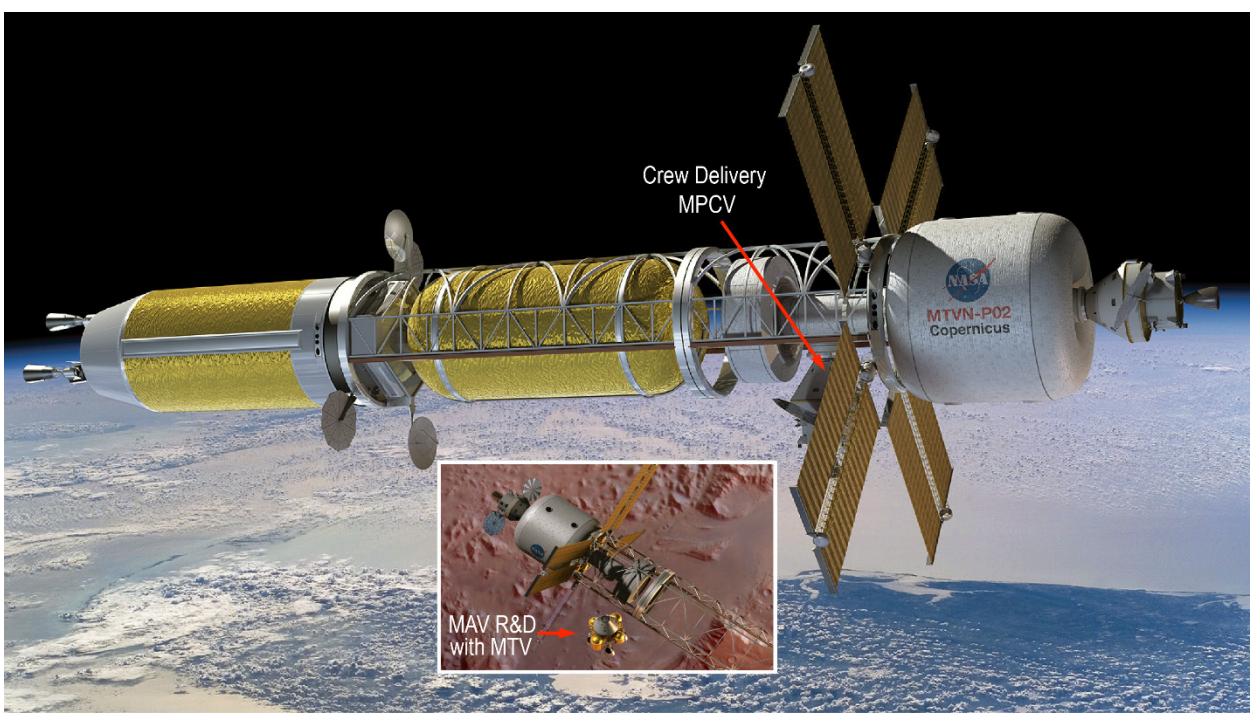

Figure 12.—*Copernicus'* TDM Provides Access to the MPCV and MAV During the Mission

6.0 *Copernicus-B*: An AG/MTV Design Option for Mars DRA 5.0

As mentioned in the Introduction, AG vehicles were ground ruled out of the DRA 5.0 study. Although sufficient contingency consumables were carried onboard to sustain the crew for up to 540 days in Mars orbit, crew fitness onboard *Copernicus* after ~2.5 years in a weightless environment was questionable. An AG version of *Copernicus*, called *Copernicus-B*, was developed by GRC shortly after the DRA 5.0 study was completed to address this deficiency. The *Copernicus-B* spacecraft is larger than its DRM 4.0 predecessor, the *von Braun*, due to key transportation system, mission and payload changes implemented between DRM 4.0 and DRA 5.0 (Ref. 14). These changes included the use of Al/Li instead of composite propellant tanks, higher DWC factors, slightly higher Mars mission ΔVs over the timeframe of interest, an ~37.5 percent increase in the TransHab mass (from ~20 to 27.5 t), a 100 percent increase in the reentry crew capsule mass (from ~5 to 10 t), plus an ~400 percent increase in the AC/EDL aeroshell mass (from ~10 to 40 t) used on each of the cargo flights. As a result of these increases, larger diameter propellant tanks (from 7.4 m to 8.4 and 10 m) and higher thrust NTR engines (from 15 to 25 klb_f) were required.

Like its 0-g counterpart, *Copernicus-B* is an in-line configuration (shown in Figure 13) that uses Earth orbit R&D to simplify vehicle assembly. Three HLV launches over 60 days are again used to deliver the vehicle's key components to LEO which include: (1) the BNTPS; (2) the integrated saddle truss and LH_2 drop tank assembly; and (3) the crewed payload. The cylindrical adaptor interfaces of the elements contain a docking mechanism, as well as all electrical and fluid connections to allow autonomous mating of the three elements in LEO. As with the NTPS, the BNTPS also includes additional external radiation shielding on each engine for crew protection during engine operation. The payload element includes the TransHab module with its six crew, the *Orion* MPCV, the TDM and contingency consumables container, plus the SST that connects the PL to the drop tank assembly. The inflatable TransHab module on *Copernicus-B* has three vertical levels oriented radial to the vehicle's spin axis (shown in Figure 5 and Figure 6). Its structural mass has also increased to accommodate the centrifugal forces it experiences during AG operation.

A noticeable difference between *Copernicus* and *Copernicus-B* is the absence of the four large and heavy (~3.5 t) PVAs. As mentioned previously, *Copernicus-B* uses its TRITON engines and a Brayton power conversion system to produce the 50 kW_e of total electrical power needed to run the spacecraft. Each engine has its own 25 kW_e BRU that is operated at 2/3rd of rated power (~17 kW_e) under normal operating continues. If an engine or BRU were lost, the remaining two units are ramped up to 25 kW_e to produce the required power level for the vehicle. The electrical power generated by the Brayton system is routed to the PL element via redundant electrical conduits attached to the sides of the long and SST assemblies. Another difference is the addition of two foldout radiator panels on the SST assembly used to radiate waste heat from the TransHab subsystems. Both the electrical conduits and foldout radiators are shown in Figure 13, Figure 14, and Figure 15.

About a week before departure, the Mars crew is delivered to LEO to begin final checkout of the spacecraft. It is anticipated that the TransHab module would be inflated autonomously but it is possible that an engineering team could be sent to *Copernicus*-B several weeks earlier to inflate the TransHab, deploy flooring and partitions, and ready the vehicle for the Mars crew to follow. Once inflated, the TransHab can provide ~500 m^3 of habitable volume for the crew. Following vehicle checkout, the engineering team re-enters its MPCV, undocks and distances itself from the *Copernicus-B* as it prepares for its 2-perigee burn departure from LEO (shown in Figure 14).

Following the TMI maneuver and subsequent short engine cool-down period, the drained in-line propellant tank is jettisoned. The low-level thrust (~100's lb_f) produced during the cool-down period lasts for several hours and is used to fine-tune the spacecraft's outbound trajectory. During this period, the crew also secures systems and equipment inside the TransHab in preparation for transitioning from 0-g to AG mode operation.

Figure 13.—BNTR-Propelled AG/MTV *Copernicus-B* in LEO Prior to TMI

Figure 14.—Following TMI and Drop Tank Jettisoning, *Copernicus-B* Transitions to AG Operation

During the initial 150-day transit out to Mars, 1-g is provided for the crew to maintain a high level of fitness. To generate this AG environment, *Copernicus-B* uses its forward and rear RCS to initiate vehicle rotation about its CM which is located ~3.6 m forward of the BNTPS. The mass of the BNTPS and its remaining ~56.4 t of LH_2 propellant is counterbalanced by the masses of the TransHab, *Orion* MPCV, contingency consumables, the TDM, and the SST. With a rotation radius of ~35.8 m, the required rotation rate (ω) is ~5 rpm. Approximately 30 days out from Mars, vehicle rotation is stopped and a final course correction burn is performed. Afterwards, vehicle rotation is again initiated but this time *Copernicus-B's* rotation rate is slowed to ~3.1 rpm to generate a centrifugal acceleration in the middle of the TransHab of ~0.38-g—equivalent to the Mars gravity field of ~3.72 m/s^2. This is done to help the crew adjust to and train for operations on the Martian surface. On final approach to Mars, the RCS is again used to terminate vehicle rotation and orient the spacecraft for its MOC burn. The RCS propellant mass used for spin-up / spin-down and MCC maneuvers during the outbound transit is ~2.43 t.

Previous and recent simulations of NTP vehicle thrust vector control (TVC) and attitude control performed by Ensworth (Ref. 36) indicate that a combination of TVC and RCS can be used to maintain stable attitudes and steer a NTP vehicle at low thrust levels following engine cool-down. They also verify that vehicle rotation about the axis of maximum mass moment of inertia is most stable and requires the least control (and RCS propellant) to counteract disturbing effects such as vehicle flexibility, propellant slosh, and astronaut movements. Estimates of RCS propellant usage from Ensworth's analyses are also consistent with estimates based on theoretical calculations of the vehicle's mass moment of inertia used in this paper. Lastly, the impact of propellant slosh was not found to be much of an issue since once vehicle rotation starts the gravity field tends to keep the fluids in place.

Following capture at Mars, the crew rendezvous with the orbiting hab lander, transfers and descends to the surface. Should abort conditions arise with either the hab lander or a major surface system, *Copernicus-B* is now available to provide the crew with shelter, life support, contingency consumables, abundant power for high data rate communications with Earth, *plus an AG environment* to maintain their health and fitness. At the end of the surface stay, the crew lifts off in the MAV with its samples and returns to the *Copernicus-B*. After verification and checkout of all spacecraft systems, the crew jettisons the MAV, then its contingency consumables and TDM, performs the TEI burn, and begins the trip home.

On the inbound transfer, *Copernicus-B* starts off with an AG environment equivalent to that of Mars. After jettisoning mass in Mars orbit and propellant performing the TEI burn, *Copernicus-B's* CM moves backward to ~32.6 m or just in front of the BNTPS. With this rotation radius, the required rotation rate to generate a centrifugal acceleration of ~0.38-g is ~3.2 rpm. After the first month, the rotation rate is increased gradually as is the g-loading on the crew by ~0.124-g per month over the next 4 months—from ~0.504 to ~0.876-g. Approximately 30 days out from Earth, vehicle rotation is again stopped and a final course correction burn is performed. When vehicle rotation resumes, it is at a higher rate of ~5.2 rpm to achieve an AG level of 1-g to help the crew readapt to Earth's gravity during the final month of the mission. The mission draws to a close during the final approach to Earth. Following vehicle spin-down, the crew enters the *Orion*, separates from the *Copernicus-B* and reenters the atmosphere while *Copernicus-B* flies past Earth at a safe distance and is disposed of into heliocentric space. The RCS propellant mass used for spin-up / spin-down and final course correction maneuvers during the inbound transit is ~1.76 t.

6.1 *Copernicus-B*'s Design Features and Characteristics

The *Copernicus-B* spacecraft has an overall length of ~83.9 m (Figure 15) and an IMLEO of ~330.6 t. Included are (1) the BNTPS (~134.4 t); (2) the saddle truss and LH_2 drop tank (~128.8 t); and (3) the crew payload section (~67.4 t). The BNTPS uses a three-engine cluster of 25 klb_f TRITON BNTR engines and

also carries additional external radiation shield mass (~6 t) for crew protection. The BNTPS uses an Al/Li LH_2 tank size of 10-m diameter by 19.7-m length. The LH_2 tank has a propellant capacity of ~87.2 t. The BNTPS also carries avionics, RCS and propellant, auxiliary battery and PVA power, docking and a reverse turbo-Brayton ZBO refrigeration system located in the forward cylindrical adaptor section. To remove ~78 W of heat penetrating the 60 layer MLI system in LEO (where the highest tank heat flux occurs), the two-stage cryocooler system requires ~8.9 kW_e for its operation. Twin circular MegaFlex PVAs on the BNTPS provide the electrical power for the ZBO system in LEO until the *Copernicus-B's* Brayton power system is brought on line prior to the TMI maneuver. At the aft end of the BNTPS, a conical extension of the stage thrust structure provides support for a common, one-sided, pumped-loop heat rejection radiator system. Enclosed within this ~71 m^2 conical radiator are three 25 kW_e BRUs (one for each TRITON engine) that operate at ~2/3rd of rated capacity and provide system redundancy. The total mass of the Brayton power system and its radiator is estimated to be ~1350 kg. The turbine inlet temperature of the He-Xe working gas is ~1300 K and the total system specific mass is ~27 kg/kW_e.

Copernicus-B's second major component is its saddle truss and LH_2 drop tank assembly. The saddle truss is a rigid, spine-like composite structure that wraps around the upper half of the LH_2 drop tank and connects the BNTPS to the forward PL element. It is ~26.5 m long and has a mass of ~13 t including docking and electrical conduits. The saddle truss is open underneath allowing the drained LH_2 drop tank to be jettisoned after the TMI burn is completed. The ~21.5 m long LH_2 drop tank has a mass of ~19.4 t and a propellant capacity of ~96.4 t. If the F/W_{eng} ratio for the TRITON engines decreases from ~5.5 to 4.0, the drop tank length and propellant capacity increase to ~22.9 m and ~103.7 t, respectively. The saddle truss length and IMLEO also increase to ~27.8 m and ~344 t.

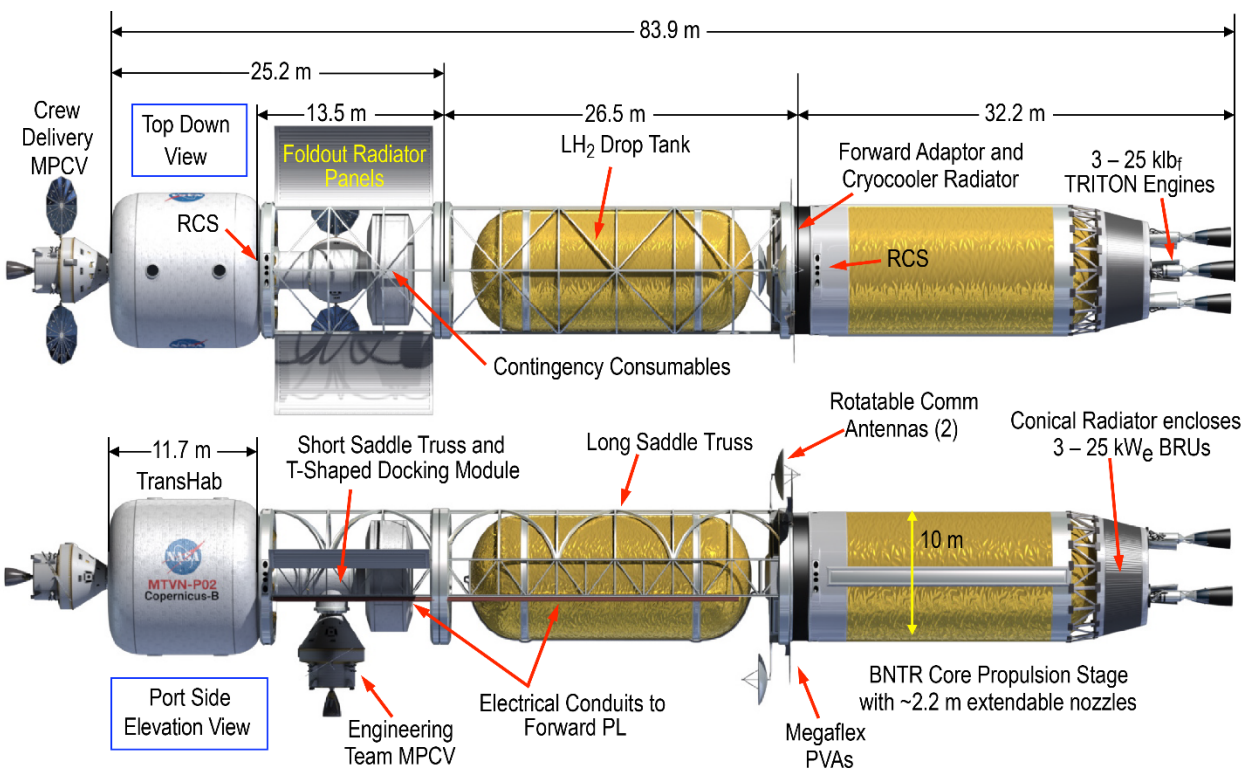

Figure 15.—Key Features and Component Lengths of the *Copernicus-B* AG/MTV

Copernicus-B's third and final component is its payload that includes the TransHab and crew, the SST, TDM and consumables container, and the *Orion* MPCV. The total crewed payload mass at TMI is ~67.4 t consisting of the following: (1) TransHab and six crew (~25.6 t); (2) SST with foldout radiators (~5.1 t); (3) TDM (~2.8 t); (4) contingency consumables and jettisonable container (~9.8 t); (5) transit consumables (~5.3 t); (6) MPCV (~13.5 t); and (7) forward RCS and propellant (~5.3 t). *Copernicus-B*'s total RCS propellant loading is ~10.8 t with the post-TMI RCS propellant load split between the BNTPS (~6.5 t) and the SST forward cylindrical adaptor ring (~4.3 t).

The requirements on total operating time, number of restarts and fuel burn-up for *Copernicus-B*'s three 25 klb_f TRITON engines are considered quite reasonable. For the round trip mission, there are four primary burns (three restarts) that use ~172.5 t of LH_2 propellant. With ~75 klb_f of total thrust and a I_{sp} of ~911 s, the total engine burn time for the mission is ~77 min (~43.2 and 10.1 min, respectively for the 2-perigee burn TMI maneuver, ~14.2 min for MOC, and ~9.5 min for TEI), well under the ~2 hr accumulated engine burn time and 27 restarts demonstrated by the NRX-XE.

Burn-up of U-235 fuel in each TRITON engine is also very low due in large part to the much higher inventory of U-235 fuel (≥ 370 kg) that exists in each engine. Assuming ~1.2 grams consumed per megawatt-day of operation, ~34 grams (~0.009 percent) are consumed during the propulsion mode and ~92 grams (~0.025 percent) during the power mode. The power mode burn-up estimate assumes 20 percent efficient Brayton power conversion and three TRITON engines operating at ~0.085 MW_t for 900 days while providing 50 kW_e of continuous electrical power.

7.0 *Discovery*: A Stretch Version of *Copernicus-B*

If only the SLS-1B upgrade and a 10 m D fairing are available to support a DRA 5.0-type Mars landing mission, then it will become necessary to add an in-line tank element to carry the required LH_2 propellant load needed to complete the mission. This four-element stretch version of *Copernicus-B*, called *Discovery* is shown in Figure 16. The results presented here assume the maximum lift capability to LEO is ~105 t. It also assumes the use of Al/Li for the BNTPS, in-line and drop tanks and a common tank diameter of 8.4 m—the same being developed for use on SLS core stage. Like *Copernicus-B*, *Discovery* is also an in-line configuration that uses Earth orbit R&D for vehicle assembly. Four SLS-1B launches over 90 days deliver the vehicle's key components to LEO.

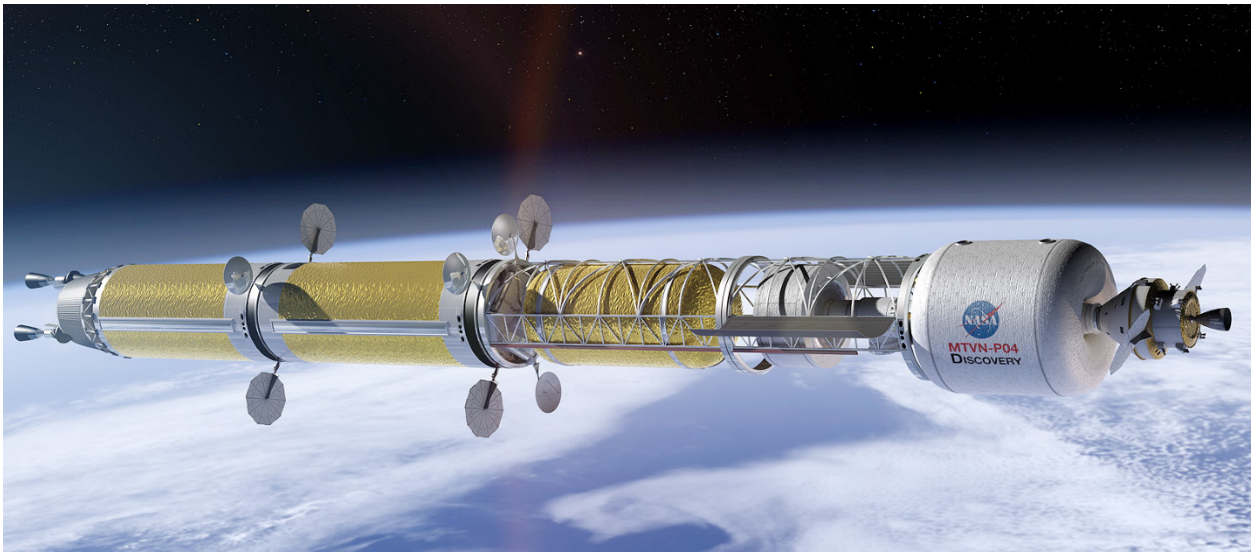

Figure 16.—BNTR-Propelled *Discovery* AG/MTV in LEO Prior to TMI

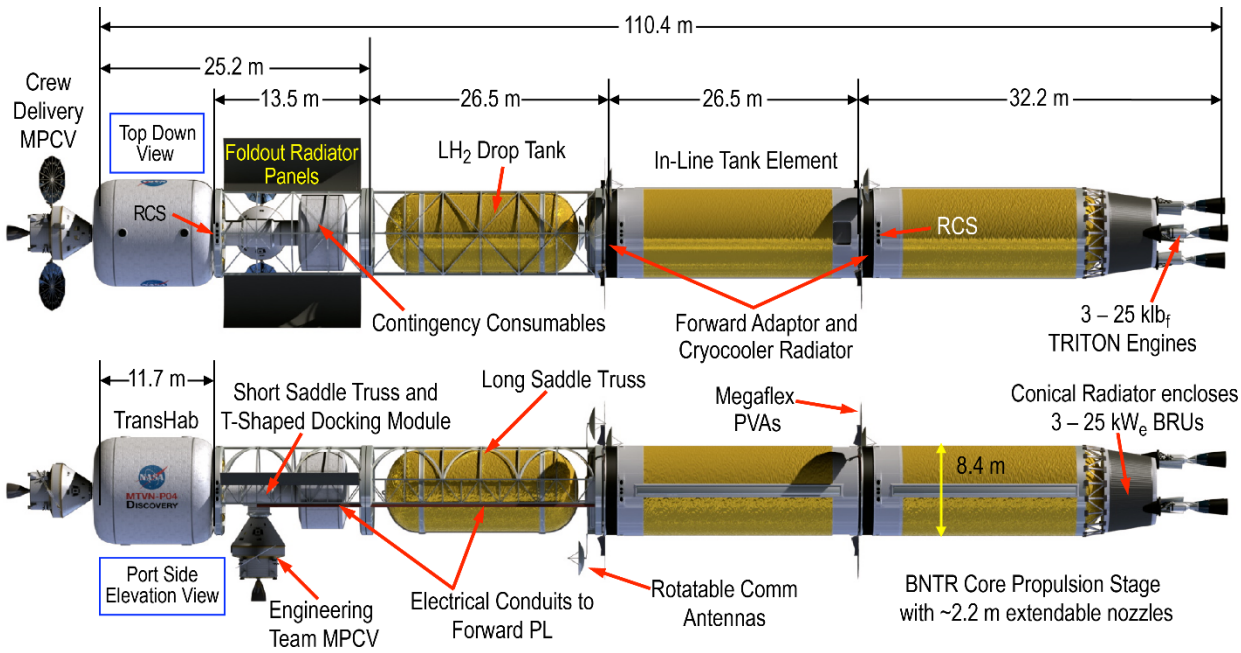

Figure 17.—Key Features and Component Lengths of the *Discovery* AG/MTV

After TMI, engine cool-down, and drop tank jettison, *Discovery* follows the same scenario of vehicle spin-up / spin-down and course correction out to Mars and back as that used on *Copernicus-B*. During the first 150 days of travel out to Mars, *Discovery* utilizes a rotation rate of ~4.38 rpm to generate a 1-g centrifugal acceleration at the TransHab location. This rate is consistent with *Discovery's* longer overall length of ~110.4 m (shown in Figure 17) and its larger rotation radius of ~46.7 m placing the vehicle CM ~12 m behind the front end of the in-line tank element during the trip out to Mars. After the final course correction burn, vehicle rotation again resumes but this time at a rate of ~2.7 rpm—sufficient to generate a centrifugal acceleration of ~0.38-g in the middle of the TransHab.

During the return trip to Earth, *Discovery* starts off with a Mars gravity environment that the crew has grown accustomed to during their long surface stay. After jettisoning mass in Mars orbit and propellant performing the TEI burn, *Discovery's* CM shifts backward to ~38 m or about 5.8 m in front of the BNTPS. With this rotation radius, the required spin rate needed to generate ~0.38-g is ~3 rpm. After the first month, the g-loading on the crew is again gradually increased by ~0.124-g per month over the next 4 months. Vehicle rotation is again stopped and a final course correction burn performed approximately 30 days from Earth. When vehicle rotation resumes, a higher rate of ~4.84 rpm is used to achieve a 1-g level for the crew during the final month of the mission.

7.1 *Discovery's* Design Features and Characteristics

As mentioned above, Discovery has an overall length of ~110.4 m (not including the MPCV) and its IMLEO is ~352.9 t. Included are (1) the BNTPS (~102.1 t); (2) the in-line propellant tank (~90.8 t); (3) the saddle truss and LH_2 drop tank (~94.8 t); and (4) the crew payload section (~65.2 t). *Discovery* uses the same TRITON engines on its BNTPS and its Al/Li LH_2 tank—with diameter and length of 8.4 by 19.7 m—has a propellant capacity of ~62.4 t. The BNTPS also carries the same subsystems as found on *Copernicus-B* but its two-stage reverse turbo-Brayton cryocooler system requires less electrical power (~7.3 kW_e) due to the smaller dimensions of the tank. As before, twin circular MegaFlex PVAs on the BNTPS provide the redundant electrical power for the ZBO system in LEO until the *Discovery's* Brayton power system is brought on line

before the TMI maneuver. Because of the smaller diameter tank used in the BNTPS, an extended conical radiator is attached to the stage thrust structure to provide the required ~71 m^2 of radiator area needed to dissipate the waste heat from *Discovery's* three 25 kW_e BRUs.

Discovery's second major element is its integrated in-line LH_2 tank and supporting systems. The in-line element has an estimated total length of ~26.5 m which includes the ~21.2 m long Al/Li tank that has a propellant capacity of ~67.7 t. Like the BNTPS, the in-line element has its own cryocooler system that requires slightly more electrical power than the core stage (~7.8 kW_e) due to its longer length. Other components included in the in-line element are the forward and rear cylindrical adaptors and docking mechanisms, avionics, RCS, auxiliary battery and PVA power, tank pressurization, propellant acquisition and feed-lines, conduits for routing electrical power from the BNTPS to forward elements that require it, plus communication antennas located at the front of the in-line element. These systems have a combined dry mass of ~17.8 t. The remaining mass (~5.3 t) is RCS propellant used predominantly for R&D maneuvers during LEO assembly.

Discovery's third major element is its saddle truss and LH_2 drop tank assembly. The composite saddle truss on *Discovery* is ~26.5 m long and it has a mass of ~13.3 t including forward and aft docking mechanisms, tank attachments and conduits for forward electrical power transmission. The ~21.1 m long LH_2 drop tank has a mass of ~14 t and a propellant capacity of ~67.5 t.

Discovery's fourth and final component is its payload that includes the TransHab and crew, the SST, the TDM and consumables container, and the *Orion* MPCV. The total payload mass at TMI is ~65.2 t consisting of the following: (1) TransHab and six crew (~24.6 t); (2) SST with foldout panel radiators (~3.6 t); (3) TDM (~2.8 t); (4) contingency consumables and jettisonable container (~9.8 t); (5) transit consumables (~5.3 t); (6) MPCV (~13.5 t); and (7) forward RCS and propellant (~5.6 t). *Discovery's* total RCS propellant loading is ~15.2 t which includes ~9.2 t used for R&D of *Discovery's* four main elements. The remaining post-TMI RCS propellant (~6 t) used for course correction and spin-up / spin-down maneuvers is split between the BNTPS (~3 t) and the SST forward cylindrical adaptor ring (~3 t).

Because of its larger mass, *Discovery* uses ~186.1 t of LH_2 propellant during the mission's four primary burns. With ~75 klb_f of total thrust and a I_{sp} of ~911 s, the total engine burn time is ~83 min (~46 and 11 min, respectively for the 2-perigee burn departure, ~15.5 min for MOC, and ~10.5 min for TEI), which remains well under the ~2 hr accumulated burn time demonstrated by the NERVA NRX-XE. Finally, U-235 burn-up in each TRITON engine continues to be minimal: ~36.7 grams (~0.01 percent) consumed during the propulsion mode and ~92 grams (~0.025 percent) consumed during the power mode.

8.0 *A.C. Clarke*—AG/MTV Using Conventional NTP and PVA Auxiliary Power

While the long, linear configuration of the *Copernicus-B* and *Discovery* spacecraft are naturally compatible with AG operation, the BNTR is considered to be a second generation engine system requiring additional engineering features in their design like the TRITON engine's ETD. Fast spectrum cermet-fueled engines also require substantially more HEU (~7 to 10 times) in their cores than do the thermal / epithermal spectrum NTR systems. Similarly, it may be difficult to use the closed, coaxial tie-tubes in the NERVA-derived composite-fueled engines as a substitute for the TRITON engine's ETD because of the tie-tube's lower operating temperatures. Bimodal engines are not the only option for AG spacecraft. Indeed, it is highly likely that initial AG spacecraft will use conventional NTP along with PVAs for auxiliary power. With its high I_{sp}, NTP can more readily accommodate the heavier payload mass and increased RCS propellant loading associated with AG operation. They can also enable shorter transit times to and from Mars thereby reducing the crew's exposure to galactic cosmic radiation and solar flares.

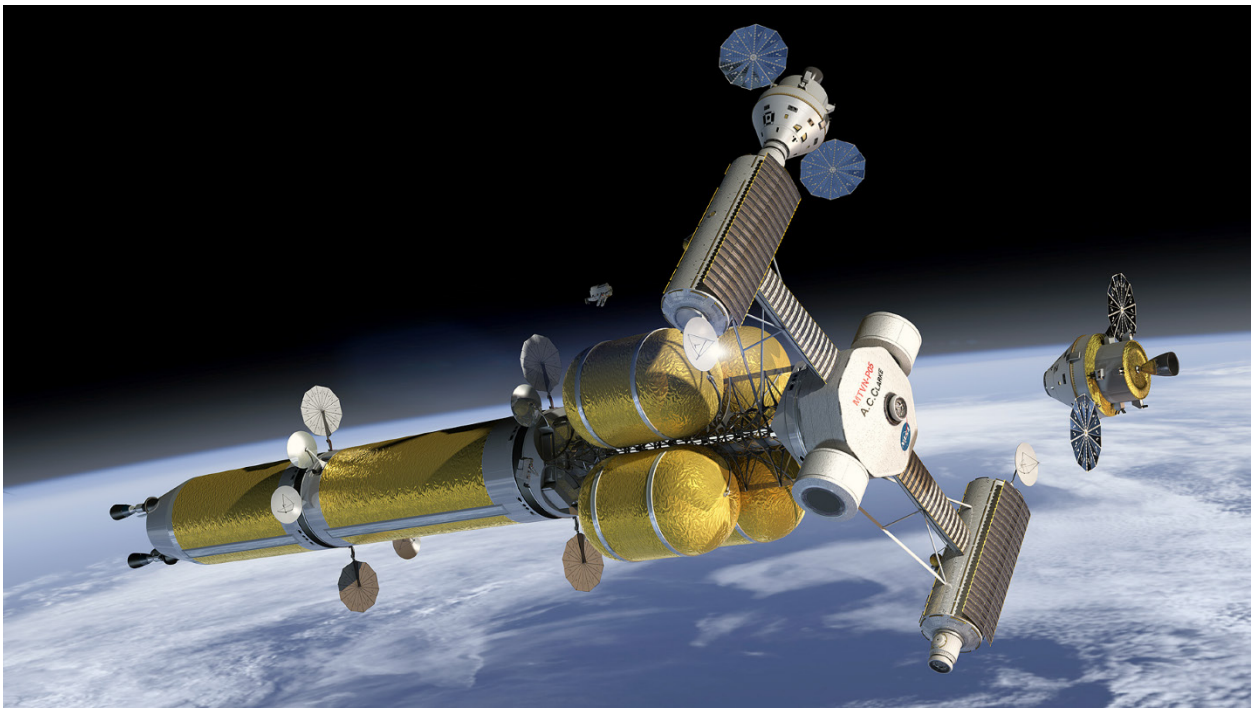

Figure 18.—NTR-Propelled AG/MTV—the *A.C. Clarke* During Final LEO Checkout

The AG vehicle design discussed in this section is a variation of the Concept 6 configuration (Ref. 8) discussed in the Introduction. Called the *A.C. Clarke* and depicted in Figure 18, it carries twin cylindrical SSF-type habitation modules whose long axes are oriented perpendicular to the longitudinal spin axis of the MTV—referred to as the Dumbbell B configuration. Its other main components include the NTPS, an in-line tank and a four-sided, concave-shaped star truss which has attached to it four LH_2 drop tanks. Like *Copernicus*, the NTPS uses three 25 klb_f composite fuel Pewee-class engines.

The 4.6 m diameter habitat modules are connected to an octagonal-shaped central operations hub located at the front of the *Clarke* via two pressurized tunnels, each ~11.5 m in length. The operations hub is ~6.4 m across the flats and the access tunnels have an outside/inside diameter of ~1.5 m/1.2 m, respectively, allowing traverse by two shirt-sleeve astronauts, or one suited astronaut at a time. Besides ladders, the pressurized tunnels also include electrical interconnect cabling plus a ventilation system including fans, scrubbers and ducts. The twin habitation modules, attached to the top and bottom of the operations hub, carry all the necessary subsystems to support a five-person crew (the same number transported in Concept 6). Nominally, the habitats accommodate two to three crewmembers, but each has excess capacity built in so that either can serve as a safe haven for the entire crew in case of an emergency. Each hab module also has its own docking port and dish antenna in a mirror image configuration that provides redundancy. The extra docking ports also provide secondary access for the engineering team's MPCV (shown attached to the upper hab module in Figure 18) or the MAV when its returns from the Mars surface. The central hub has its own primary docking located at its front, and attached to its port and starboard sides are two contingency food containers of equal mass (also shown in Figure 18).

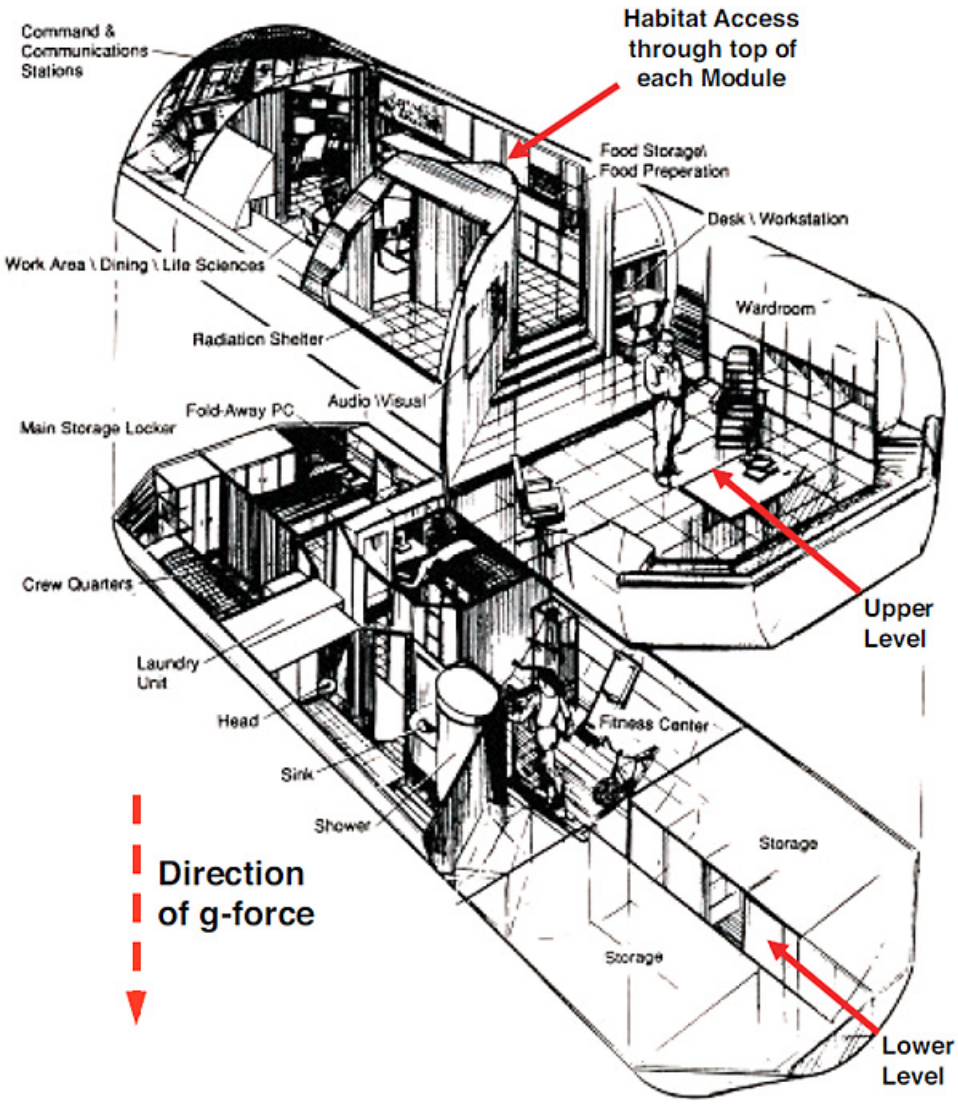

Figure 19.—*A.C. Clarke* Habitat Interior Arrangement

Figure 19 shows one possible arrangement for the interior of an individual habitat module used on the *Clarke*. To minimize habitat mass, the access tunnels enter directly into the top of each habitat module via pull-down ladders. This internal arrangement provides command displays that are transverse to the longitudinal axis of the module, allowing left-right head movement in the desired direction of motion. Transverse bunks may also help alleviate toss-turn movement disturbances during sleep. When moving in the direction of spin, apparent body weight increases will be experienced but can be dealt with through purposeful exertion like walking uphill. In the Dumbbell A vehicle configuration, the long axes of the hab modules are oriented parallel to the spin axis of the vehicle with the accompanying benefits discussed by Loret (Ref. 17) and outlined in Figure 5.

Each hab module also includes one crew compartment whose walls are thickened to hold supplies (e.g., food, LSS consumables, and/or waste products) that provide a minimum of 20 g/cm^2 of shielding. This cabin is used as the radiation shelter for all module crewmembers in the event of a solar flare. It is expected that on the order of six solar flare events will occur during the course of *Clarke's* 900-day mission.

Mounted to the Sun-facing side of the tunnels and the habitat modules is a PVA power system (see Figure 18) that includes ~30 m^2 of array area over each transfer tunnel and ~75 m^2 over each hab module. The resulting ~210 m^2 of array area provide ~26 kW_e of electrical power (~8.1 m^2/kW_e) in Mars orbit or a little over 5 kW_e per crewmember.

The *Clarke* utilizes Earth orbit R&D to assemble the NTPS, in-line tank element and the star truss. The PL components (logistics hub, tunnels and hab modules along with their PVAs) are then delivered to LEO on a single SLS-1B launch where they are then attached to the front of the star truss. The logistics hub is attached first and is then pressurized. Using the hub's teleoperated robotic arm, the tunnels are connected next followed by the two habitat modules. Because the habs are fully independent systems, they can be activated immediately after launch. They can then be attached using either the robotic arm or flown and docked to the tunnels using the AG RCS thrusters attached to each module. Side struts stowed on the star truss are then deployed, attached to the hab modules and locked into place. Afterwards, two final SLS-1B launches are used to deliver a set of paired LH_2 drop tanks that are attached to the star truss and its connecting fluid feed lines.

When fully assembled, the Mars crew arrives and together with the engineering team performs a final vehicle checkout. The engineering team then departs and the *Clarke* begins its 2-perigee burn TMI maneuver (depicted in Figure 20). Drop tank sets are jettisoned at the end of the first perigee burn (shown in Figure 21) and the second perigee burns. As before, low-level cool-down thrust produced over several hours after TMI is used to fine-tune the *Clarke's* outbound trajectory. During this period, systems and equipment inside the two hab modules are secured by the crew in preparation for vehicle spin-up and AG mode operation.

Figure 20.—The *A.C. Clarke* Departing LEO at the Start of TMI

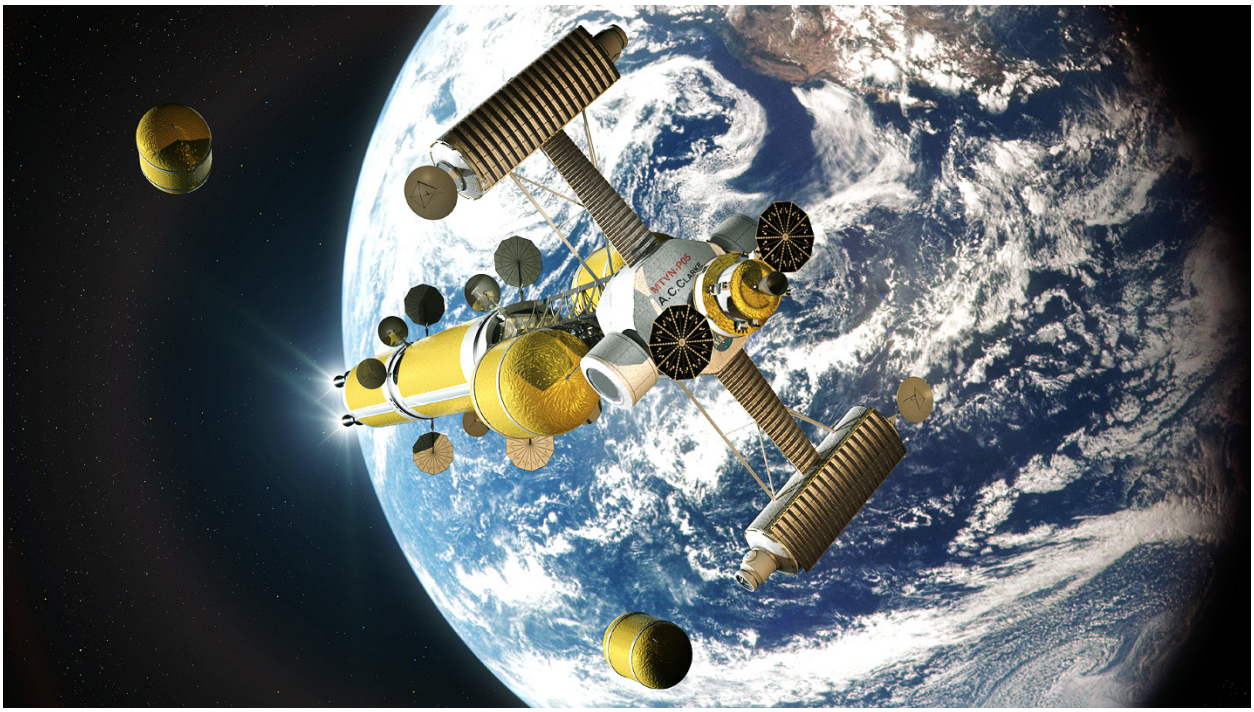

Figure 21.—Drop Tank Jettisoning at the End of the First Perigee Burn

In contrast to the bimodal vehicles, *Copernicus-B* and *Discovery*, which rotate about their CM and perpendicular to their flight vector, the *Clarke's* front end and PVAs are pointed towards the Sun during the transit out to Mars and the vehicle's longitudinal / spin axis is oriented perpendicular to its flight path as shown in Figure 22. The rotation radius for the *Clarke* is ~17 m measured from the center of the operations hub to the floor of each habitat module (see Figure 23). With this rotation radius, a centrifugal acceleration equivalent to Mars surface gravity (0.38-g) can be produced with spin rate of ~4.5 rpm. At 6 rpm, the AG environment is ~0.68-g. A lunar gravity environment of ~0.167-g can be produced at just under 3 rpm. To produce the same 1-g environment for the crew as *Copernicus-B* and *Discovery* during the initial 150-day transit out to Mars, a spin rate of ~7.25 rpm will be required which is higher than the nominal 6 rpm recommended by Stone (Ref. 18) and Thompson (Ref. 19) but well below the 10 rpm rotation rate test subjects were exposed to during the Pensacola studies discussed in Section 2.0. By extending the length of the *Clarke's* star truss, the transfer tunnel lengths can be increased allowing a lower rotation rate while keeping the hab modules within the protected radiation-free cone provided by the engine's external shields.

About 30 days out from Mars, the RCS thrusters on each of the *Clarke's* hab modules will again be fired to stop vehicle rotation and a final course correction burn will be performed. When vehicle rotation is again initiated the spin rate will be ~4.5 rpm to produce ~0.38-g and help acclimate the crew to Mars' gravity field.

Following capture into Mars orbit, the Clarke uses its cool-down thrust to rendezvous with the orbiting hab lander. The crew then transfers over to the lander, initiates EDL near the cargo lander and begins the surface exploration phase of the mission. At the end of the surface stay, the crew lifts off in the MAV with their samples and returns to the *Clarke* docking at one of the two ports available on the hab modules. After verification and checkout of all spacecraft systems, the crew jettisons the MAV, the two contingency consumable containers attached to the opposite sides of the logistics module (shown in Figure 18 and Figure 23), then performs the TEI burn to begin the trip home.

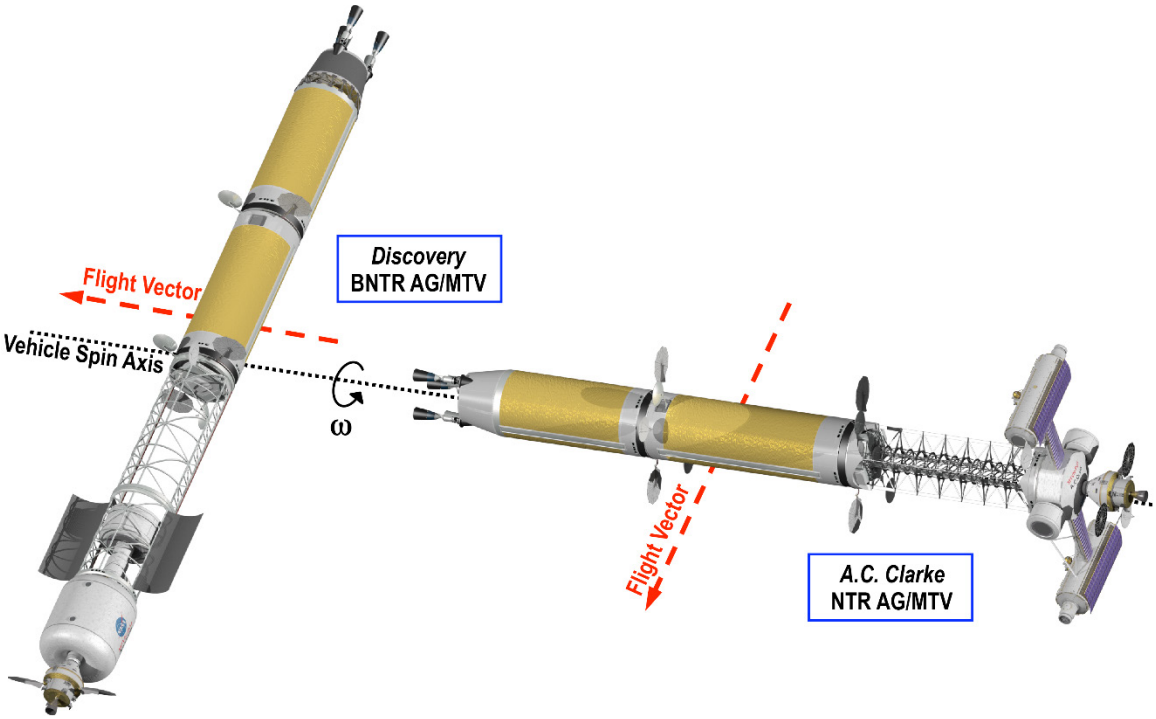

Figure 22.—Flight Path and Rotation Differences Between *Discovery* and *A.C. Clarke* AG/MTVs

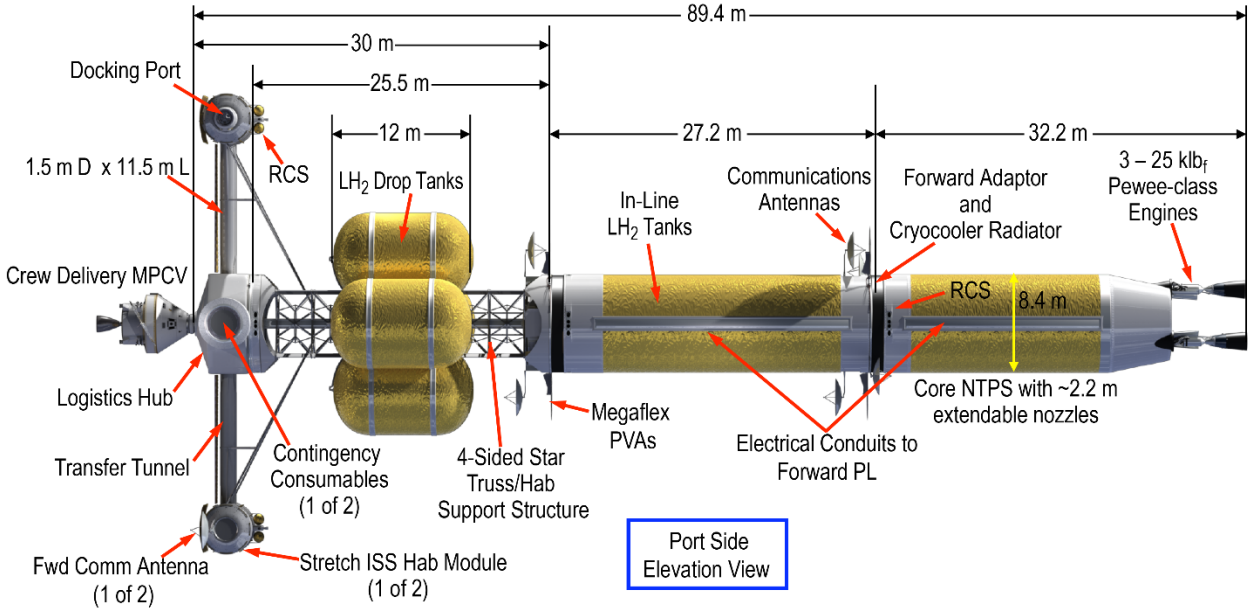

Figure 23.—Key Features and Component Lengths of the *A.C. Clarke* AG/MTV

During the return trip to Earth, the *Clarke* starts off with a spin rate of 4.5 rpm to provide the Mars gravity environment that the crew is accustomed to. After the first month, the spin rate is again increased incrementally—from ~5.15 to ~6.79 rpm—to increase the g-loading on the crew by ~0.124-g per month over the next 4 months. After the final course correction burn, a spin rate of ~7.25 rpm is used during the final month of the mission to help the crew readapt to Earth's gravity before re-entry and landing. Following vehicle spin-down, the crew enters the *Orion* and re-enters the atmosphere while the *Clarke* flies past Earth for final disposal into heliocentric space.

8.1 *A.C. Clarke's* Design Features and Characteristics

The *A.C. Clarke* has an overall length of ~89.4 m (Figure 23) and an IMLEO of ~480 t. Included are (1) the NTPS (~100 t); (2) the in-line tank element (~95.8 t); (3) the star truss and four LH_2 drop tanks (~197.5 t); and (4) the crew payload section (~86.7 t). The NTPS uses a three-engine cluster of 25 klb_f composite fuel Pewee-class engines and also carries additional external radiation shield mass (~6 t) for crew protection. The NTPS uses an Al/Li LH_2 tank with an outer diameter of 8.4 m and length of 19.7 m. The LH_2 tank has a propellant capacity of ~62.4 t. The NTPS also carries avionics, RCS and propellant, auxiliary battery and PVA power, docking and a reverse turbo-Brayton ZBO refrigeration system located in the forward cylindrical adaptor section. Twin circular MegaFlex PVAs located at the forward end of the NTPS provide the electrical power (~6.5 kW_e) required for operating the two-stage cryocooler system in LEO. The in-line tank has a length of ~22.2 m and a propellant capacity of ~71.6 t. It too has a ZBO system at its front end plus PVAs that supply the ~7.2 kW_e needed to operate it.

The four-sided star truss on the *Clarke* is ~25.5 m long and attached to it are four drop tanks that carry ~141.4 t of LH_2 propellant. Each tank carries ~35.4 t of propellant and is ~12 m in length. The drop tanks which use only passive MLI are jettisoned in pairs after the first and second perigee burns (shown in Figure 21) to reduce vehicle mass and propellant consumption during the TMI maneuver.

The *Clarke's* payload element is ~21.5 t heavier than that carried by *Discovery*. It includes (1) twin habitat modules and onboard systems (~42.2 t); (2) five crew and suits (~1.0 t); (3) the central logistics hub (~7.2 t); (4) connecting tunnels and hab support brackets (~5.5 t); (5) consumables used in transit (~4.4 t); (6) contingency consumables packaged in two external containers (~8.1 t); (7) the MPCV (~13.5 t); and (8) the RCS and propellant used for spin-up/spin-down activities (~4.8 t). The Dumbbell A configuration for the *Clarke* (shown in Figure 24) has its hab modules oriented parallel to the vehicle's spin axis and requires additional structure to support the PVAs deployed between the central hub and the hab modules. It is expected to have a comparable size and slightly heavier mass.

With its larger mass, the *Clarke* uses ~254.2 t of LH_2 propellant during its primary propulsion maneuvers. With ~75 klb_f of total thrust and a I_{sp} of ~906 s, the total engine burn time is ~112.9 min (~47.3 and 34 min, respectively, for the 2-perigee burn departure, ~18.7 min for MOC, and ~12.9 min for TEI), which remains under the ~2 hr accumulated burn time of the NRX-XE. The maximum single burn duration of ~47.3 min is also well under the 62 min record set by the NRX-A6 engine (Ref. 13). Finally, U-235 burn-up in each of the *Clarke's* engines continues to be minimal: ~52.7 grams (~0.14 percent) consumed during the four primary propulsion maneuvers.

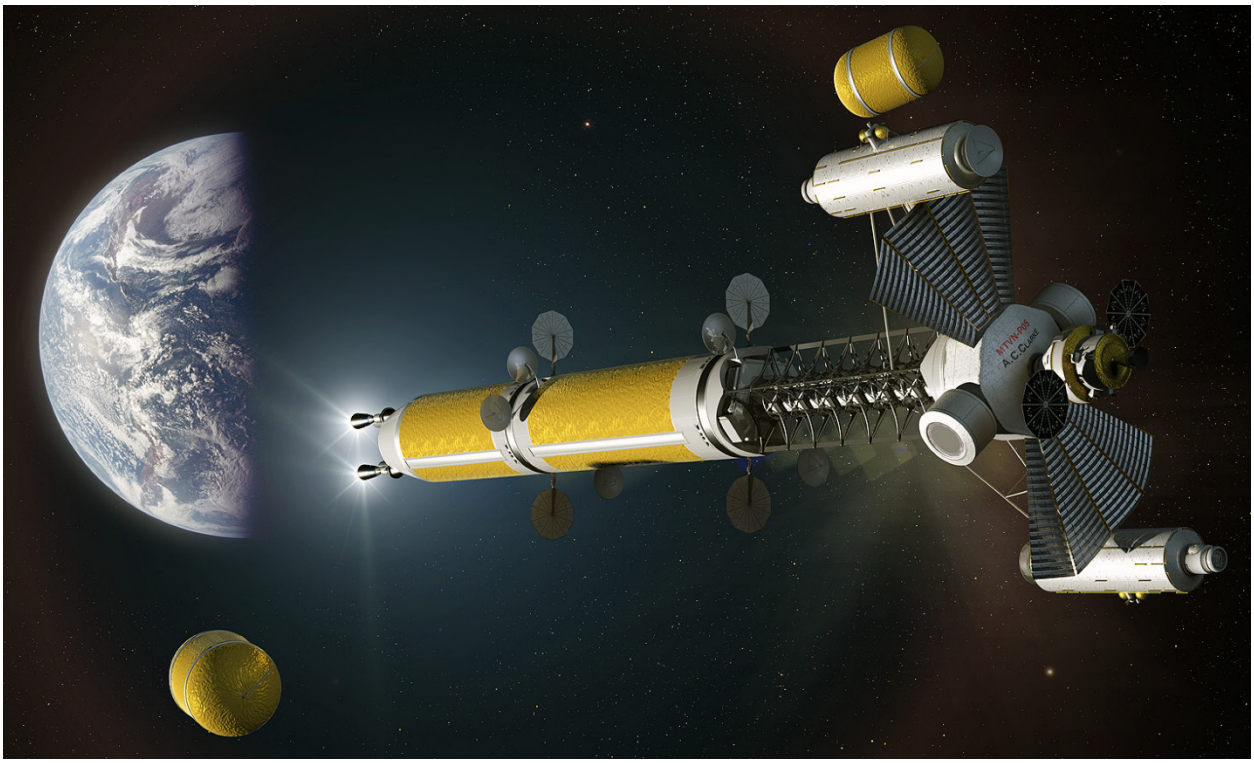

Figure 24.—*A.C. Clarke-A* jettisons Final Drop Tank Set at End of the Second Perigee Burn.

9.0 Summary and Conclusions

More than 50 years of human spaceflight have provided a wealth of knowledge on the physiological effects of long-term exposure to 0-g. Significant adverse effects include loss of muscle mass (back and leg muscles) and the progressive loss of skeletal bone mass (from the lower vertebrae, hip and femur). Another significant effect is fluid redistribution to the upper body that may be responsible for changes in vision and eye anatomy referred to as VIIP. In view of these problems and recognizing that exercise and use of pharmaceuticals alone are unlikely to counter the anticipated effects, an AG spacecraft offers many advantages and may indeed be an enabling technology for human flights to Mars.

A number of important human factors must be taken into account in designing an AG spacecraft and in the selection of the rotation radius, spin rate, and orientation of the habitation module or modules. These factors include the gravity gradient effect, radial and tangential Coriolis forces, along with cross-coupled acceleration effects. A number of AG spacecraft concepts have been proposed in the past using aerobraking and chemical propulsion, tethers, electric propulsion, and NTP. Of these options, the NTR is the most attractive. It is a proven technology with a high thrust and high I_{sp} (~100 percent higher than LOX/LH_2 chemical rockets) capability that is particularly attractive for AG missions allowing it to more readily accommodate the heavier payload mass and increased RCS propellant loading required for multiple spin-up/spin-down cycles.

Conceptual designs for AG/MTVs using both BNTP and NTP have been presented. The *Copernicus-B* and *Discovery* designs use TRITON bimodal engines and Brayton power conversion to generate 10s of kilowatts of spacecraft electrical power during the mission coast phase eliminating the need for large PVAs. Both spacecraft designs use a single inflatable TransHab crew module with multiple vertical floors oriented radial to the vehicle's spin axis. The configuration of the *Copernicus-B* and *Discovery* spacecraft designs—long and linear—is also naturally compatible with AG operation. When using the SLS-1B launch vehicle,

with lower lift capability and smaller diameter fairing, an extra in-line tank must be added. This adds length to the *Discovery* thus lowering its required spin rates for a given acceleration level. By rotating the vehicles about their CM and perpendicular to their flight vector at spin rates of ~2.7 to 5.2 rpm, a centrifugal force and AG environment corresponding to ~0.38 to 1.0-g can be established to help maintain crew fitness out to Mars and back, also while in Mars orbit in the event of a surface abort. While operationally attractive from a vehicle standpoint, the bimodal engines used on the *Copernicus-B* and *Discovery* spacecraft are more complex and viewed as a second-generation system. They also require a significantly larger inventory of HEU in their reactor cores.

As shown in this paper, bimodal engines are not the only option for AG spacecraft. In fact it is more likely that initial designs will use conventional NTP along with PVAs to supply auxiliary power. The *A.C. Clarke* is such a design. It carries twin cylindrical ISS-type habitat modules with their long axes oriented perpendicular to the longitudinal spin axis of the vehicle. The twin habs are connected to a central operations hub located at the front of the spacecraft via two pressurized tunnels that provide an ~17 m rotation radius. With spin rates of ~4.5 to 7.25 rpm, a centrifugal force of ~0.38 to 1.0-g can be established at the center of the habitat modules. Approximately 210 m^2 of PVA area is also mounted to the Sun-facing side of the *Clarke's* hab modules and tunnels that can supply ~26 kW_e of crew and spacecraft electrical power while in Mars orbit. It is also possible to orient the hab modules parallel to the *Clarke's* longitudinal spin axis that is expected to provide additional human factor benefits.

Finally, it is important to remember that long duration deep space missions will also expose the crew to galactic cosmic radiation and multiple solar flare events. Using NTP, shorter transit times to and from Mars are also possible reducing the crew's total exposure during the mission. Today, NTP technology is receiving increased attention. NASA's Advanced Exploration Systems (AES) program restarted an NTP technology development and demonstration effort with its Nuclear Cryogenic Propulsion Stage (NCPS) project in FY12 (Ref. 34). This initial 3-years Phase I effort (FY12 to 14) will be followed by a Phase II effort in FY15 to 17 involving fuel element irradiation testing and possible non-nuclear, subscale validation testing of the SAFE (Subsurface Active Filtration of Exhaust) borehole ground test option at the Nevada Test Site. If successful, this effort could be followed by major system-level technology demonstrations that include ground testing a small (~7.5 klb_f), scalable NTR by 2023, followed by a flight test of a small NTP stage in 2025.

Appendix—Acronym List

AB	aerobrake
AC	aerocapture
AES	Advanced Exploration Systems
AG	artificial gravity
Al	aluminum
AMBR	Advanced Material Bipropellant Rocket
ARC	NASA Ames Research Center
B_4C	boron carbide
Be	beryllium
BeO	beryllium oxide
BNTP	Bimodal Nuclear Thermal Propulsion
BNTPS	Bimodal Nuclear Thermal Propulsion Stage
BNTR	Bimodal Nuclear Thermal Rocket
BRU	Brayton Rotating Unit
CM	center-of-mass
CVD	chemical vapor deposition
D	diameter
DM	docking module
DRA	Design Reference Architecture
DRM	Design Reference Mission
DWC	dry weight contingency
EDL	entry, descent and landing
EMO	elliptical Mars orbit
ETD	energy transport duct
FE	fuel element
FY	fiscal year
g	Earth's gravitational field (~9.807 m/s^2)
Gd_2O_3	gadolinium oxide
GG	gas generator
GRC	NASA Glenn Research Center
hab	habitat
He	helium
HEU	highly enriched (93%) uranium-235
HLV	Heavy Lift Vehicle
IAA	International Academy of Astronautics
IMLEO	initial mass in low Earth orbit
ISRU	in situ resource utilization
ISS	International Space Station
klb_f	thrust (1000's of pounds force)
L	length
L/D	lift to drag
LEO	low Earth orbit
LH_2	liquid hydrogen
Li	lithium

LOX	liquid oxygen
MAV	Mars Ascent Vehicle
MCNP	Monte Carlo N-Particle
MDAV	Mars Descent/Ascent Vehicle
MLI	multilayer insulation
MOC	Mars orbit capture
MOCS	Mars orbit capture stage
MPCV	Multi-Purpose Crew Vehicle
MTV	Mars transfer vehicle
NAR	nozzle area ratio
NCPS	Nuclear Cryogenic Propulsion Stage
NERVA	Nuclear Engine for Rocket Vehicle Application
NRX-XE	NERVA eXperimental Engine
NSBRI	National Space Biomedical Research Institute
NTP	Nuclear Thermal Propulsion
NTPS	Nuclear Thermal Propulsion stage
NTR	Nuclear Thermal Rocket
PVA	photovoltaic array
R&D	rendezvous and docking
RCS	Reaction Control System
SLS	Space Launch System
SNRE	Small Nuclear Rocket Engine
SOFI	spray on foam insulation
SRHC	short-radius human centrifuge
SRR	Slow Rotating Room
SSF	Space Station Freedom
SST	short saddle truss
t	metric ton (1 t = 1000 kg)
TDM	transfer tunnel with docking module
TEI	trans-Earth injection
TEIS	trans-Earth injection stage
TMI	trans-Mars injection
TPA	turbopump assembly
TPS	Thermal Protection System
TRITON	TRImodal capable, Thrust Optimized, Nuclear
TRL	technology readiness level
TT	tie tube
TVC	thrust vector control
U	uranium
UO_2	uranium dioxide
VIIP	Visual Impairment due to increased Intracranial Pressure
W	tungsten
W-Re	tungsten rhenium
Xe	xenon
ZBO	zero-boiloff
ΔV	velocity change increment (km/s)

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