Construction of an International Space Transit Vehicle Using the Space Station

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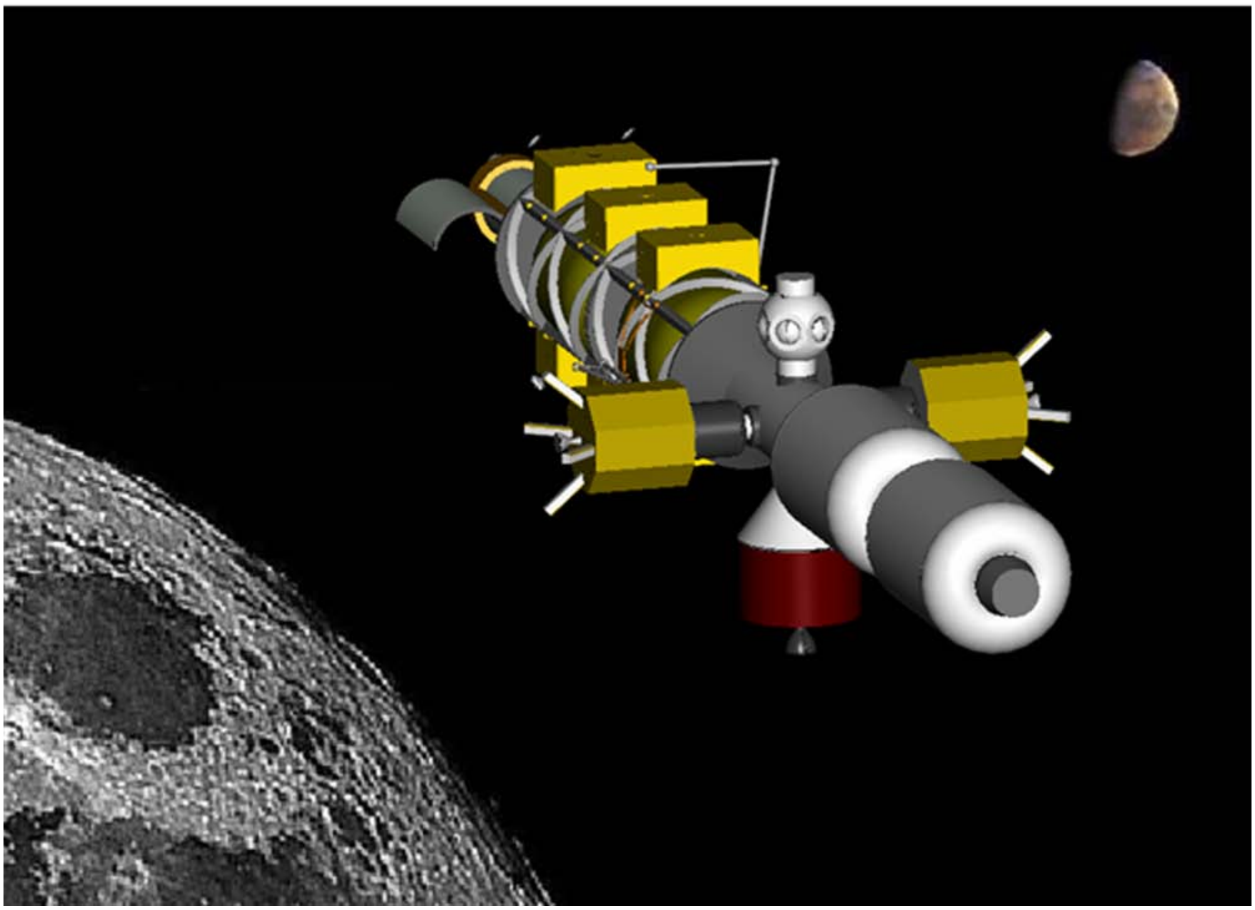

Figure 1: ISV in Space

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Abstract

After abandoning the possibility of directly evolving the ISS for cislunar, lunar orbital or interplanetary applications, we looked at the potential of the ISS as the prime and opportune assembly node for such missions beyond LEO. We note that space station concepts in the past have referred to such a facility in LEO for this purpose; a manned station in LEO to build large vehicles and structures for outbound destinations, since such systems cannot be lofted directly from the Earth, using current technology.

The International Space Vehicle (ISV), as shown in figure 1, is a concept architecture for a new kind of spacecraft presented here as the initial platform for evolving systems for space exploration and extraterrestrial settlement goals set by the U.S. and shared by the world; namely manned return to the Moon and manned missions to Mars and beyond. The nature of these missions, using current technology, demand long duration manned space presence for several years. No vehicle built or planned yet, with the partial exception of the ISS, which requires constant logistics support from Earth, can effectively support life in space for such periods.

The ISV will be constructed at the ISS, leveraging the facility's robotic arm, EVA capabilities, full-time crew supervision and mission control support, as well as the experience in on-orbit integration gained by the construction of the ISS. The candidate ISV stack will be optimized for travel beyond LEO and long term survival in space with the proper radiation shields, artificial gravity, and nuclear power to sustain a closed loop life support system, initially, for up to three years. Three distinctly separate manned vehicle systems are proposed to make up the ISV stack. They include this ISV cislunar/interplanetary transit vehicle, an earth to orbit and re-entry vehicle and an extraterrestrial lander vehicle. The ISV is portrayed as a large stack, not designed for resisting large thrusting or braking forces required for high energy velocity changes during extraterrestrial touchdowns or Earth return. Therefore, lander vehicles docked to the ISV will carry humans to lunar and planetary surfaces and a capsule will ferry astronauts from Earth to the ISV and back as well as serve as an escape system in case of a mission abort.

After construction and certification at ISS, the ISV will perform a multi-year Earth-Moon cycling mission, where it will survive in cislunar space and support multiple long term sorties to the lunar surface. During this mission all of the systems, methods, and hard data obtained beyond LEO will be used to conduct deep space manned missions using the ISV or its evolved derivatives.

The ISS will be essential for construction of the ISV, both as an on-orbit assembly platform and as a heritage design from which to innovate. The ISV will be constructed by integrating ISS-like modules which will be designed and built by a coalition of nations. The scale of this vehicle (comparable to ISS) will require U.S. leadership and international unity and will open unprecedented opportunities for space exploration for all of humanity.

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The Mission

In the fall of 2009 the Review of United States Human Space Flight Plans Committee, also known as the Augustine Commission, released its findings after a six month evaluation of the U.S. manned space program. Along with recommendations on how to extend International Space Station (ISS) operations beyond 2016, the committee proposed three options for the direction of exploration beyond low earth orbit (LEO) which were as follows [Augustine,N. etal., 2009]:

1) Mars First – all effort focused on mars landing perhaps using the Moon as a system proving ground

2) Moon First – all effort focused on lunar exploration and development with the goal of building a Mars expedition capability

3) The Flexible Path – develop systems to explore many destinations in the inner solar system including lunar orbit, Lagrange points, near earth objects and the moons of Mars with the eventual exploration of the Moon and Mars.

Although all three options were presented in the final report, two goals are clearly favored. The flexible path is highlighted as the best strategy for manned space exploration both by the committee and political leadership. In addition, the committee recognized the large investment in the construction of the ISS and presented options for extending ISS operations beyond 2020.

The concept presented in this paper directly leverages the ISS hardware and experience to construct a new type of space vehicle that is optimized for long duration flexible operations beyond LEO as well as lunar and interplanetary missions.

Historical Success

The Crew Exploration Vehicle (CEV) is an obvious return to the Gemini/Apollo era capsules that were so successful in accomplishing many of the "firsts" of human space exploration. Following the extremely complex and expensive, but very capable shuttle, there are many good arguments that can be made for a simpler and less expensive design such as the CEV. The CEV as described by President Bush in his "Vision for Space Exploration" (VSE)would primarily be designed for travel beyond LEO to the Moon and Mars as well as ferry astronauts to and from the ISS. Although far less complex than the shuttle, the CEV still carries with it some very large inefficiencies.

A spacecraft such as the CEV is designed to do quite a few things. It must first be launched from Earth carrying crew, then travel beyond LEO to complete a mission, followed by travel back to Earth at which point it must safely survive atmospheric reentry. The burden of reentry greatly reduces mission performance, habitable volume and mission duration when compared to a spacecraft designed to remain and operate exclusively in space such as the ISS. Even removal of the requirement for excursions beyond LEO greatly increases the capabilities of the vehicle in LEO as can be seen with the shuttle. In short, designing the CEV to accomplish every aspect of a space exploration mission (with the exception of a surface landing) forces the design to be vastly sub-optimized for nearly all of the mission profiles and requirements.

The ISS Example

The International Space Station(ISS) has demonstrated several key technologies and capabilities that have the potential to play a large role in the future direction of human space exploration. Advancements in on-orbit system integration during the construction of the ISS represent a huge a capability of which the ISV concept presented takes full advantage. Module docking, EVA operations and robotic arm support for EVAs and manipulation were all routinely utilized and developed during ISS construction. Advances in spacecraft maintenance and methods to preserve human health in microgravity have also been made during ISS operation. Finally, there are 20+ years of design lessons (across national borders) that can be leveraged for future on-orbit assembly projects.

The ISS also contains many program and diplomatic advancements that should be included in any international effort. The ISS contains major components built in five different countries and a coordinated on orbit integration led by the U.S[Logsdon, J.M., 1998] The concept presented in this paper requires international support and the lessons and diplomatic relationships resulting from the ISS construction form a strong foundation on which to build a program to execute this concept.

The present ISS configuration clearly shows a Russian segment and an US and allied partners segment. At first, we debated splitting the ISS configuration at end-of-life and thrusting the US and allied segment toward the Moon. When we realized that the ISS international partnership model dictated that we build upon the current configuration(and not detract from it), it became apparent that the promising option is to use the ISS and all the modular assembly in low Earth Orbit experience gained from its buildup to create the next facility employing a new level of sophistication in international collaboration[Thangavelu, 1993]. Thus the concept for the International Space Transit Vehicle was born. Ironically, the history of the space station informs that in the early concepts, projected by NASA's Office of Long Range Plans as well as independent studies of major aerospace contractors, the primary purpose of the station was to be a facility to assemble and commission large spacecraft and structures using the talents and experience of crew in EVA, to be then raised up into higher orbits or sent to further destinations, as the mission plans dictated.

At the outset, several configurations from the literature on interplanetary vehicles were reviewed. Since artificial gravity was seen as a requirement, all designs employing zero G were eliminated. Those left included the Russian design from 1989, the SICSA cable tethered design, the Mars transit hotels and more recently the nuclear stacks proposed by Stan Borowski and others. Cable structures were considered unreliable, and therefore the design concept narrowed to those with a strong back, capable of retaining integrity under both compressive and tensile forces, while rotating to create artificial gravity. Large habitable volume and long duration life support systems were also considered requirements for this vehicle. Use of the NASA inflatable TransHab technology was incorporated into the design to achieve large pressurized volumes while the University of Arizona Lunar Greenhouse design was leveraged to create a bio-regenerative life support system. These “next generation” space technologies have been blended with the extensive ISS heritage to create the International Space Transit Vehicle.

II. The International Space Transit Vehicle Concept

The proposed International Space Transit Vehicle (ISV), shown in figure 2, is very different from many traditional manned space systems and instead draws its heritage primarily from the ISS. With the incorporation of several next generation space technologies this ISS derivative carries the capability to support a crew of six for three years in space without re-supply from earth. Orion class crew capsules and surface access vehicles can carry crew from the ISV to earth, other space platforms and the surface of celestial bodies. This implies that the primary ISV elements will remain in orbit for the life of the vehicle which allows the system to be optimized for long duration space missions much like the ISS. Large habitable volume, artificial gravity, bio-regenerative life support and nuclear power are such optimizations that support long manned deep space missions and all have been incorporated into the ISV concept.

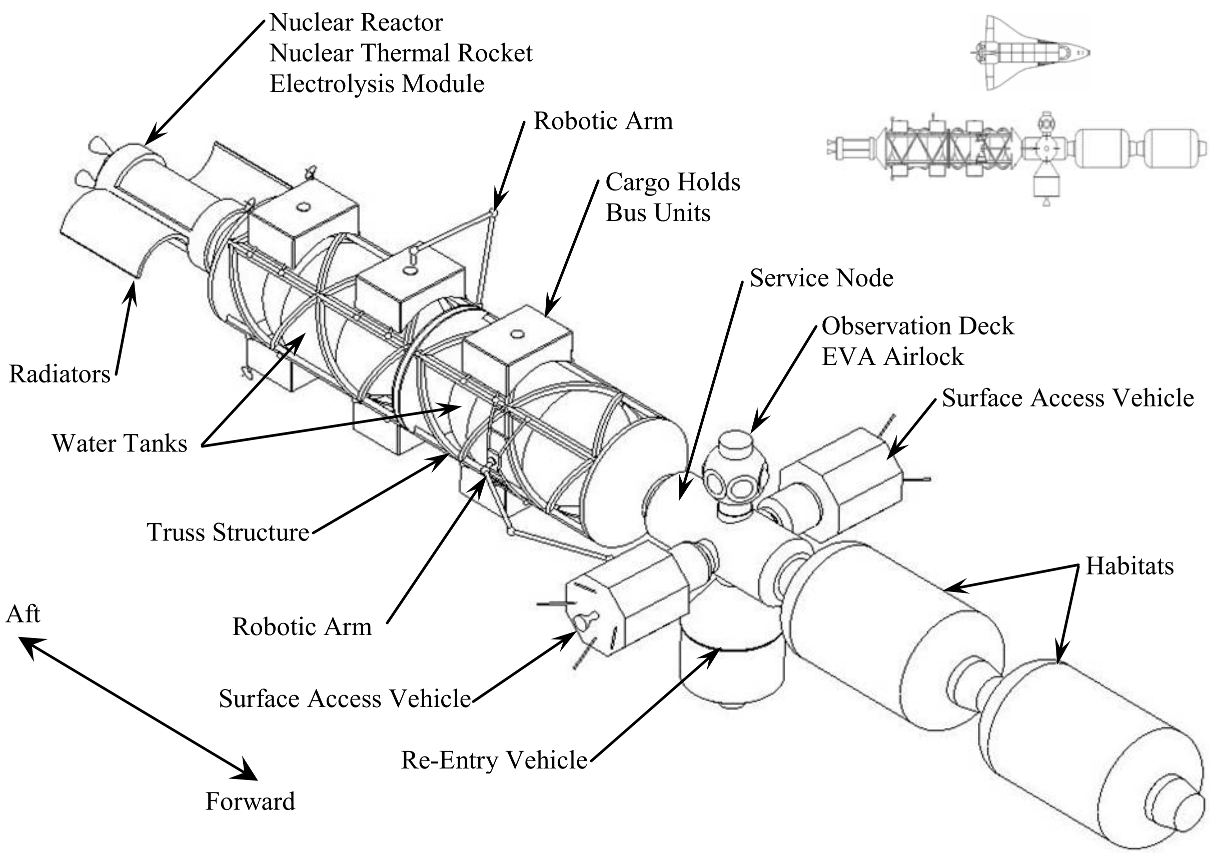

Figure 2: ISV – Basic Configuration

Habitable Volume

Given the long mission durations (up to three years) that the ISV will perform, human factors such as crew physical and mental health are a critical consideration for this architecture. Although the Celentano curve, shown in figure 3, predicts that required habitable volume per crew member asymptotes at 20 m^3 for long missions[NASA STD 3000, Booher 1992], empirical evidence (figure 4) suggests that the required volume is much higher[Cohen, 2009]. The strong correlation between mission duration and habitable volume, shown in figure 4, demonstrates that the requirement for an ISS class mission is between 100 and 500 cubic meters per crew with the ISS providing approximately 100 m^3 per crew member. The ISV will provide approximately 150 m^3 of habitable volume per crew member by utilizing inflatable habitat architecture and external cargo holds for un-pressurized storage and bus units.

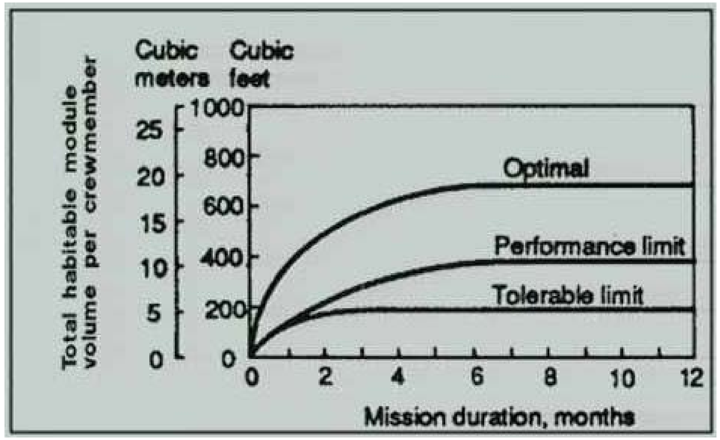

Figure 3: The Celentano Curve

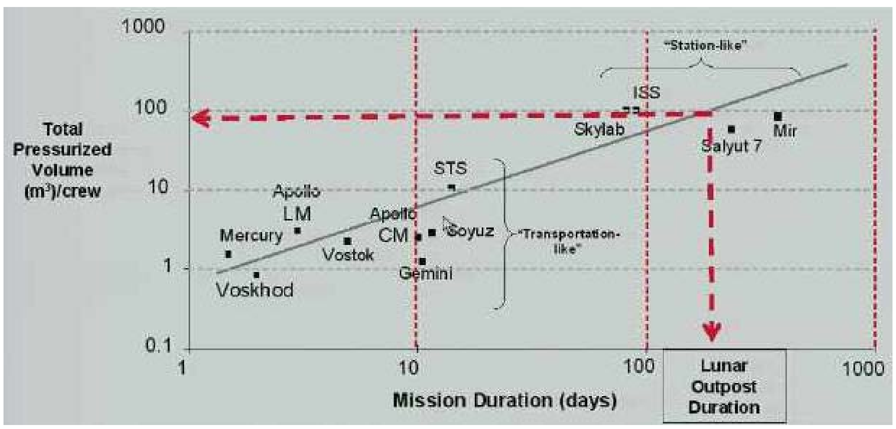

Figure 4: Spacecraft Pressurized Volumes

The primary pressurized volume for crew quarters and operations is provided by two transit habitat modules (TransHab) originally developed and tested by NASA in the late 90s[Schrimpsher, D.,2006]. TransHab is an inflatable structure packed tightly against a solid core structure to fit inside a 5m fairing (figure 5). In orbit, Transhab expands to an 8.2m diameter cylinder that would provide 340 m^3 of habitable volume [Kennedy,K., 2002]. The nearly two dozen layer outer shell provides protection from deep space thermal and radiation environments while the central core provides the load bearing structure during thruster burns. TransHab has already undergone significant development in which prototypes were built and shown to withstand impacts from hyper velocity particles simulating micrometeorites. Additional pressurized volume is provided by the service node, observation deck, and docked vehicles. The aggregate pressurized volume for the entire vehicle is approximately 900 m^3 as seen in appendix A.

Figure 5: TransHab Module

Service Node

The structural bridge between the un-manned truss/tank aft side of the vehicle and the pressurized volumes of the TransHab modules and secondary vehicles is a hard shell structure identified as the service node (SN). The SN, shown in figure 6, is a 5m diameter hard structure with 4 docking ports around its circumference, a single pressurized tunnel at the forward end and an un-pressurized structural port at the aft end. The SN provides the structural load path for all docked vehicles as well as the observation deck during NTR burns.

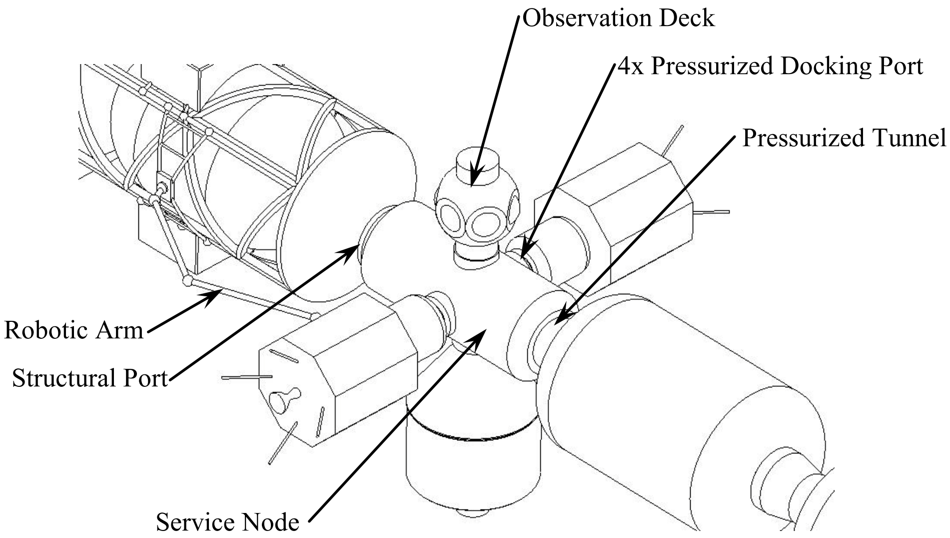

Figure 6: Service Node

Through the SN, crew will be able to access all secondary vehicles docked to the ISV as well as transfer from the TransHab modules to the observation deck airlock. The SN is within reach of the ISV's robotic arm system which allows the system to capture secondary vehicles and facilitate their docking to the SN. Access to the robotic arm system also makes the SN region ideal for EVA operations which will be initiated thru the observation deck airlock.

Observation Deck

The observation deck (OD) serves several critical functions of the ISV. The bottom portion of the OD is connected to the SN thru a structural pressurized tunnel allowing access to the OD. The top of the OD is a pressurized docking port / airlock. During ISV assembly this port will be docked to the ISS while during operations it will be used as the airlock passage to outer space for EVA operations. The OD also provides panoramic views of the ISV and outer space. This visibility will be useful for operation of the robotic arm system, vehicle docking and EVA support. The OD may also be utilized as an area for crew make scientific observations or to relax and view the solar system unobstructed by the earth's atmosphere or stack components.

Robotic Arm System

The ISV will be equipped with two robotic arms capable of traveling laterally across the truss structure similar to the remote manipulator system on the ISS as well as the shuttle robotic arm. Both systems have been used very successfully to complete a variety of tasks including docking, satellite capture, EVA assistance and vehicle inspection. The ISV robotic arm system will be capable of all these functions as well as provide the capability to capture approaching vehicles at the ISV's center of rotation, as shown in figure 7, and slowly manipulate them to the service node's docking ports as described in previous sections. The system will also facilitate removal of items from the outer storage compartments and placing them into the airlock at the top of the observation deck as shown in figure 8. The outer storage compartments will also contain bus units such as control moment gyros and power conditioning and distribution systems. Should these systems require repair or replacement, the robotic arm system will provide the EVA support to accomplish these tasks.

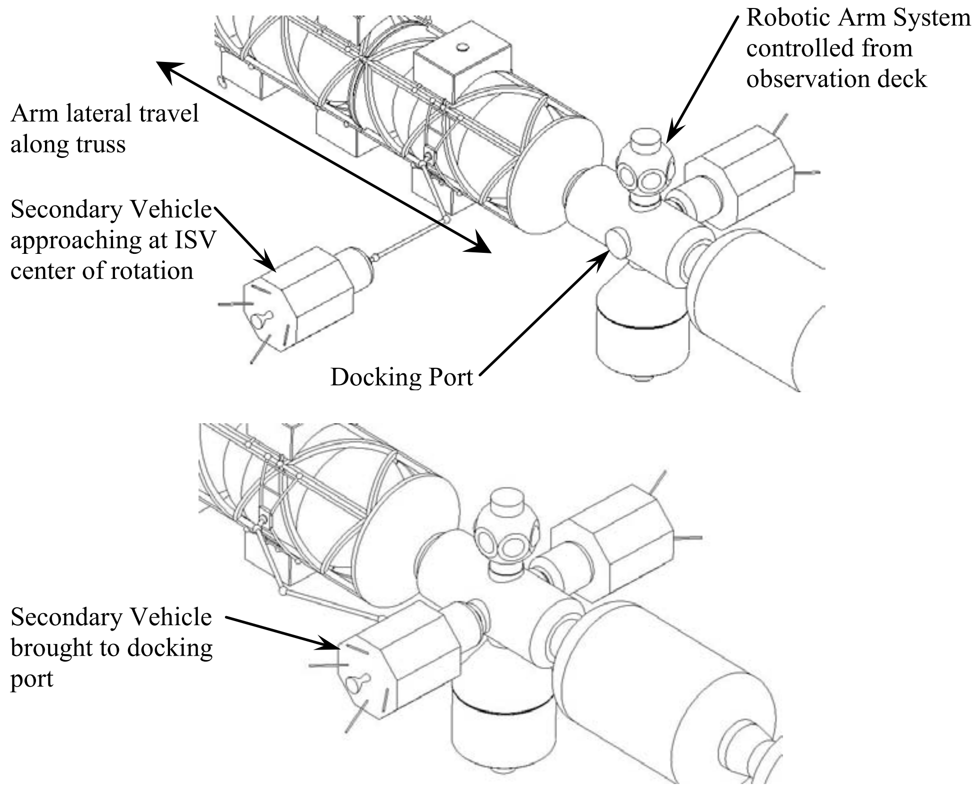

Figure 7: Robotic Arm System Capture of Secondary Vehicle

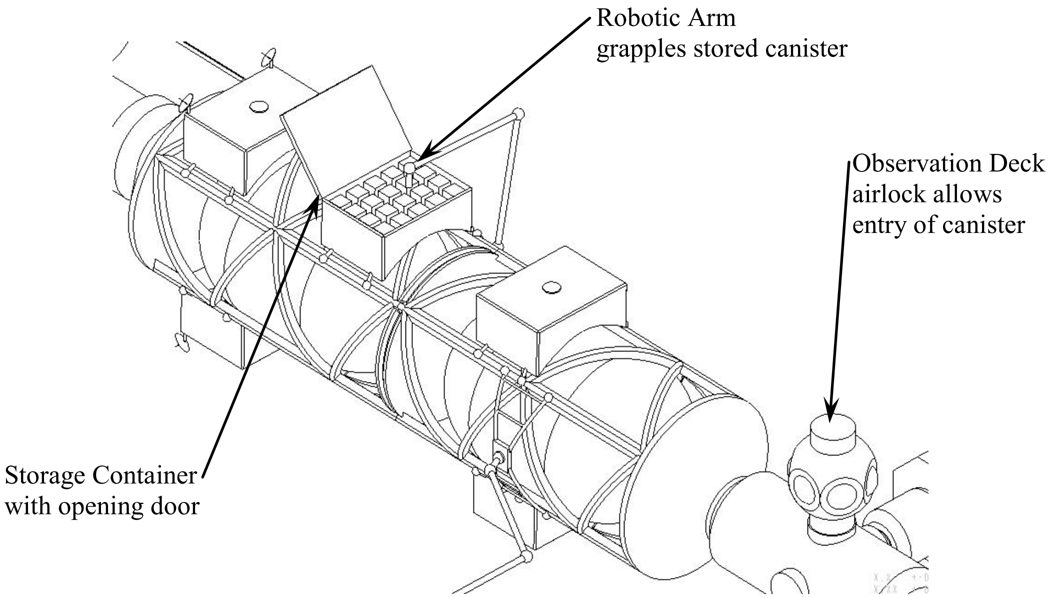

Figure 8: Storage Compartment and Bus Unit

The ISV robotic arms will provide video feedback during usage but will also be mostly visible from the observation deck from which they will be controlled. Their mobility along the tank truss structure allows the arms to access most of the vehicle which allows for extensive EVA support during vehicle integration and for repairs during operations. Lessons learned from the shuttle and ISS programs have shown that robotic arm manipulator systems have proven invaluable during large LEO assembly projects. Figure 9 shows a drawing of one such system utilized on the ISS.

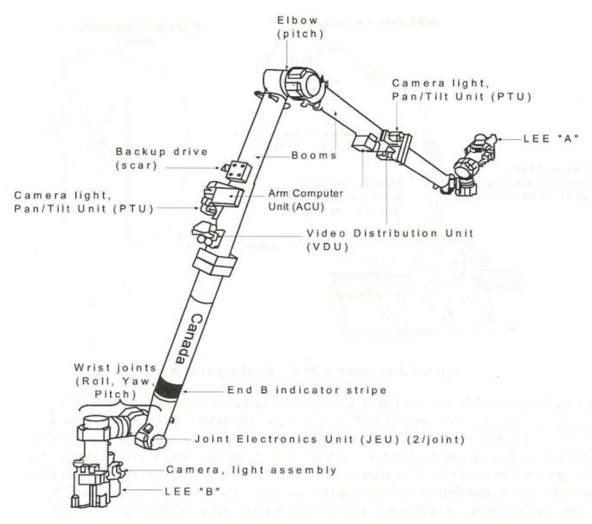

Figure 9: ISS Canada Arm

Nuclear Propulsion and Power Generation

The ISV will contain a nuclear reactor to power a nuclear thermal rocket and Brayton cycle power generation system to satisfy all propulsion and electrical power requirements. Nuclear thermal rockets (NTRs), developed by the United States NERVA program (1959-1972) can provide ISPs up to 1000 s while exerting thrusts of 25,000-210,000 lbs [Gunn, S., Robinson E.,2009]. The ISV NTR will only be used in orbit and therefore shall be optimized for the high ISP, low thrust (~25,000 lbs) and multiple restarts, all demonstrated by the NERVA program.[Gunn, S., 2009]

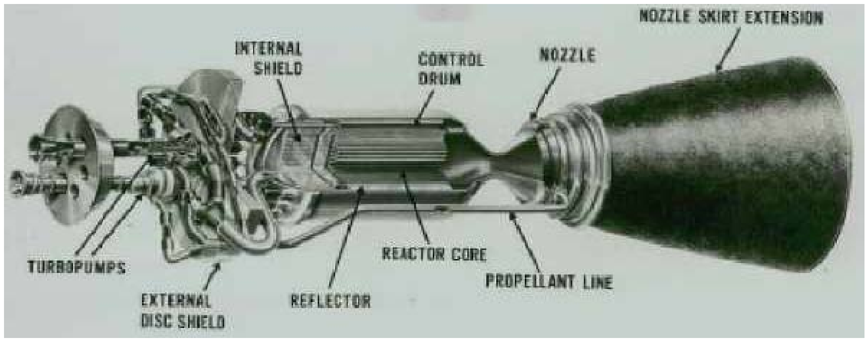

Figure 10: NERVA Nuclear Rocket Configuration

In his research on "bimodal" nuclear thermal rocket technology, Stanley Borowski shows that NTR systems such as the NERVA engine (figure 10) offer an opportunity for dual use of the nuclear reactor to generate electrical power as well as thrust[Borowski, S. etal.,1999, 2001]. A traditional NTR system can be architected to include a separate working fluid to run a Brayton cycle power generation system in which 50 KW of electrical power can be created at the expense of 300 KW of dissipated thermal energy.

Fuel from Water

The ISV nuclear system is further modified to include a water electrolysis center in which water is separated into H_2 and O_2 to be used as propellant for the NTR. Therefore, no cryogenic fluids need to be stored and can simply be generated from water in the short term prior to immediate use during delta V burns of the NTR. This concept circumvents the need for large tankage, cryogenic storage and handling, including long term management issues like boil-off that is associated with several earlier proposals. A separate working fluid runs through a Brayton cycle power generator to provide the electrical power for the electrolysis center as well as the bus and payload systems. The system architecture is shown in figure 11.

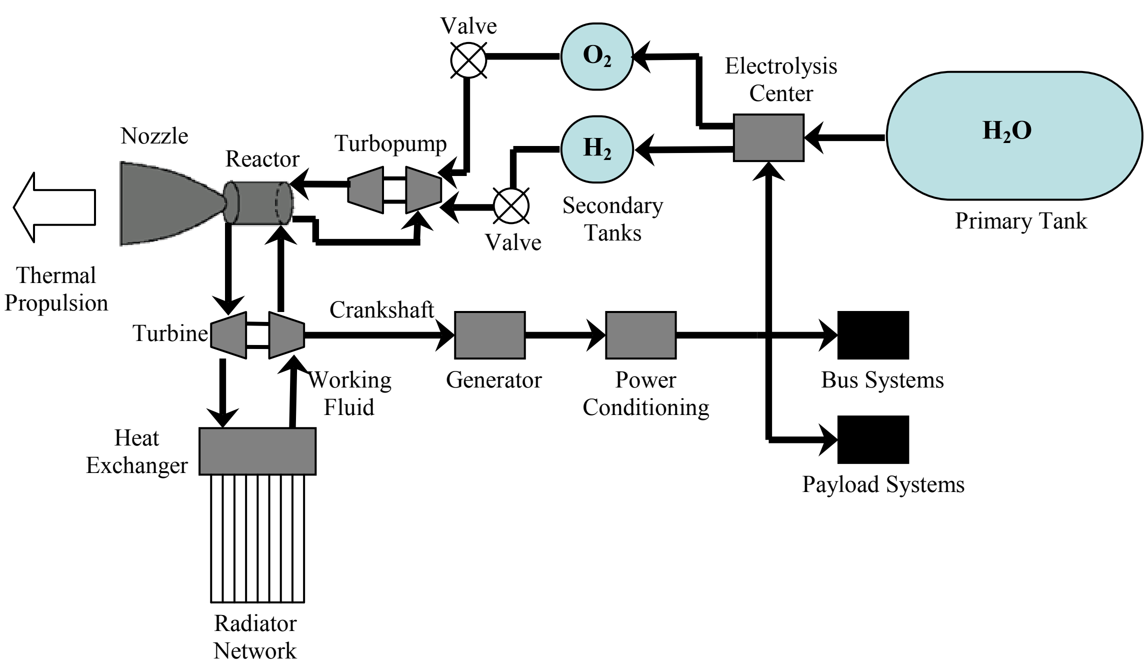

Figure 11: Nuclear System Schematic

The Brayton cycle power generation system will dissipate 300 KW of heat which can only be achieved through the ISV radiator network. Two curved deployable radiators, similar to the shuttle payload bay radiators, enclose the nuclear node of the ISV. During high power generation periods, the deployable radiators will open (figure 12) and, combined with the exposed body of the nuclear node, can achieve ~134 m^2 of effective radiator area. At 200 °C this area can dissipate over 300 KW of heat. The deployable radiators will close as required to scale heat dissipation with the heat load demands during different mission phases. Intermittent insolation of the radiators due to stack rotation may affect heat rejection and could be minimized by solar shields or by optimizing rotation plane during transit.

$$Q = \sigma \varepsilon A T^4$$

$$A = \frac{300{,}000W}{\left(5.67^{-8}\,\dfrac{W}{m^2K^4}\right)\cdot(.85)\cdot(473^4K^4)} = 124.4m^2$$

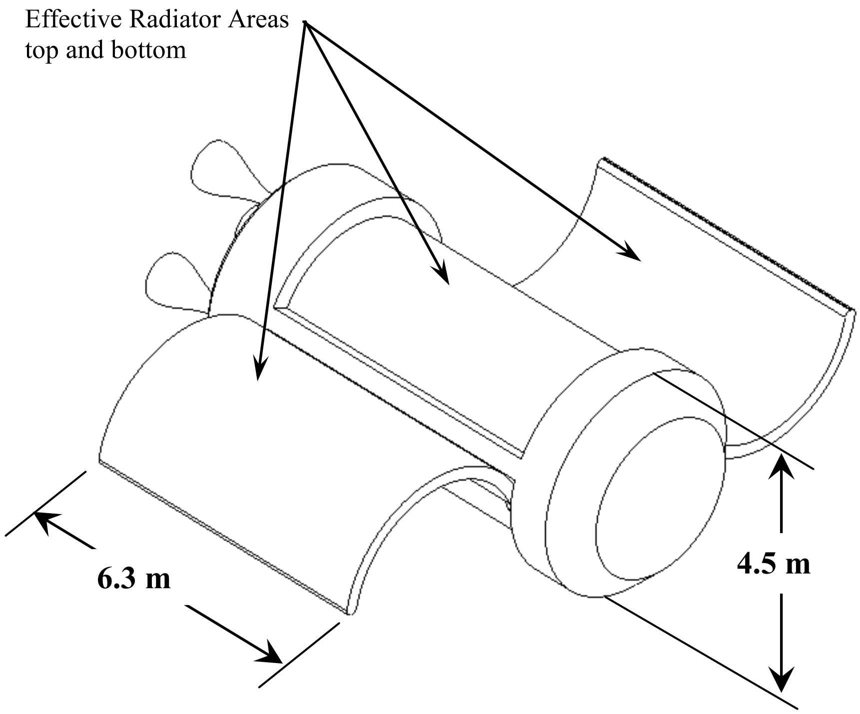

Figure 12: Nuclear Node Deployable Radiators

Shielding the crew from nuclear thermal rocket(NTR) radiation exposure is achieved using three design parameters. Placement of the nuclear node at the far aft end of the truss geometrically reduces the radiation threat by simply reducing the angle of view. The large distance between the nuclear node and the primary crew habitats narrows the angle of view and thus shrinks the amount radiation along the emitted cone that intersects the habitats as shown in figure 13. The second method of shielding is provided by the tank truss segments of the ISV. Numerous large structural elements of the truss as well as the tanks themselves provide radiation barriers between the nuclear node at one end and the habitable volumes on the other. Finally, the tanks themselves hold one of the best known radiation shields: water. During the beginning and middle phases of the mission the tanks hold immense amounts of water providing a near perfect radiation shield cone. Margin in the delta V budget allows for a significant amount of water to be left over even after the final NTR burns which can provide additional protection even during the last mission phases. All crewed long duration mission vehicles must be fully prepared to mitigate solar storms. A toroidal water jacket built around the interconnect of the two inflatable habitats(not shown) further provides a radiation storm shelter for crew during anomalously large solar particle events arising from unpredictable solar coronal mass ejections(CMEs) that may sweep over the spacecraft as it transits cislunar or interplanetary space .

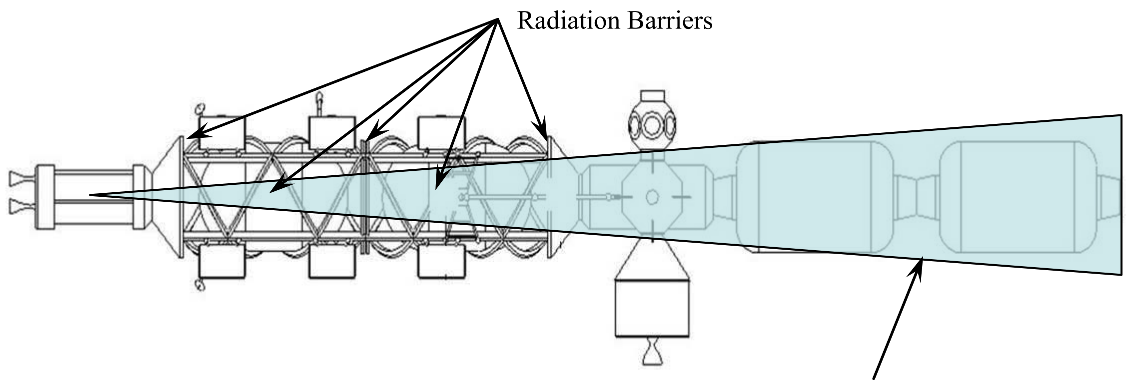

Figure 13: Radiation Shielding

It must be recognized that the radiation shielding cone design implemented on the ISV only protects the crew of the ISV and will not shield approaching or close proximity spacecraft. During docking/un-docking and close proximity encounters the nuclear node must be shut down temporarily unless other solutions to this challenge are implemented.

Delta V

Since the nuclear thermal rocket (NTR) system of the ISV does not depend on combustion to create chamber pressure, the system need only be provided a stream of molecules to energize. As demonstrated above, the system uses an electrolysis center to separate water into hydrogen and oxygen which are utilized separately as propulsion for the NTR. As proven by the American NERVA program, ISPs of nearly 1000s can be achieved using hydrogen molecules as an NTR propellant[Gunn, S.,.2009]. The assumption is made that an ISP of 450s can be reached using the heavier oxygen molecules thru the NTR. Two 8m tanks each 14m long carry a total 1,139,150 kg of water. Storing water does not require any special refrigeration as cryogenic fluids do and allows for denser storage of hydrogen then storing pure hydrogen. Once split by electrolysis the hydrogen and oxygen molecules propelled thru the NTR can provide up to 9.3 km/s of delta V with the current tank configuration and vehicle mass estimates shown in the appendix. This system performs much better than nuclear-heated steam propulsion proposed by Zuppero.[Zuppero etal., 1997]

$$M_{propellant} = M_H + M_O = \frac{1}{9} M_{H_2O} + \frac{8}{9} M_{H_2O}$$

$$ISP_{blend} = \frac{1}{9} ISP_H + \frac{8}{9} ISP_O = \frac{1}{9}(1{,}000s) + \frac{8}{9}(450s) = 511s$$

$$\Delta V = ISP \cdot g \cdot \ln\left(\frac{M_{propellant}}{M_{ISV}} + 1\right) = (511s) \cdot \left(9.81\frac{m}{s^2}\right) \cdot \ln\left(\frac{1{,}139{,}150kg}{212{,}600kg} + 1\right)$$

$$= 9275\frac{m}{s^2} = 9.3\frac{km}{s^2}$$

Approximately 8 km/s are required for a journey from LEO to low lunar orbit and back which gives the ISV operating margin for lunar missions as well as the ability to refuel secondary vehicles for multiple surface visits. Larger delta Vs are required for Mars missions, however they are still within ISV capabilities as the vehicle could be scaled to include larger tanks as required for desired missions. A primary aspect of the ISV design is that the spacecraft can be refueled with water in LEO between missions and that water can be split into its constituents which can then be used to propel the spacecraft through the NTR or to fuel secondary vehicles such as the surface landers. This system architecture permits simple refueling operations of the ISV with an inert fuel thus allowing a single vehicle to be re-used for multiple missions. Reliable, in-space restart capability is assumed for engines.

Artificial Gravity(AG)

Experience from bone and muscular atrophy of the ISS crew suggests that artificial gravity at some fraction of earth's gravity is likely required to sustain healthy human activity in space for long duration missions [Joosten, K.2002, Ball &Evans 2001]. The ISV design provides artificial gravity forces during long transit phases of the mission by spinning the entire length of the vehicle about the spacecraft center of mass as shown in figure 14.

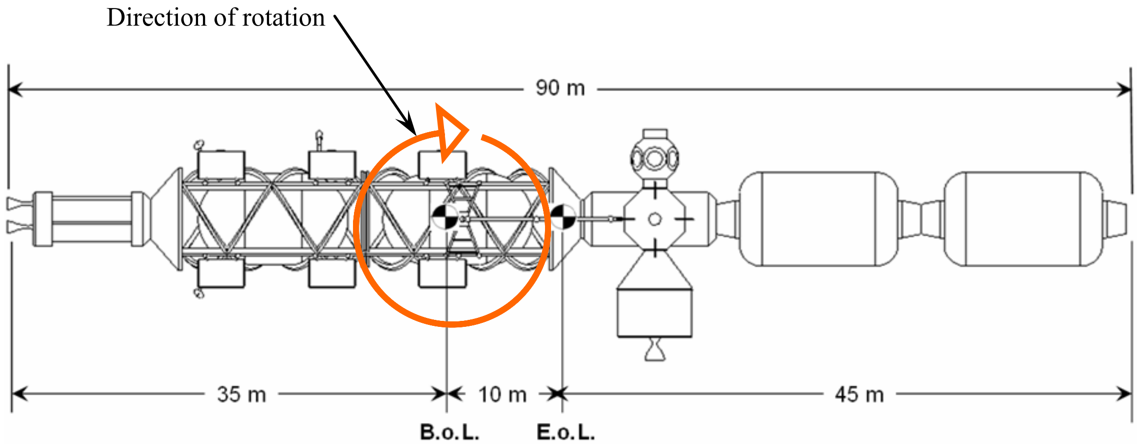

Figure 14: Center of Mass Spin Axis

Initial designs considered the possibility of counter rotating sets of hab modules to create AG but were abandoned due to reliability issues. Rotating the entire stack structure about its high moment of inertia axis provides the largest possible distance between the axis of rotation and the TransHab modules where the crew will spend the majority of their time. This reduces the influence of the coriolis effect as well as allows relatively high artificial gravity forces to be achieved with low rates of spin. Although the vehicles center of mass will shift as propellant is used, the effective radius of rotation can be maintained at ~20-40 meters which allows for up to 1/2 G of realized force by spinning the vehicle at 5 rpm. Rotation of the vehicle will be achieved by angling the thrust vector of the nuclear thermal rocket through gimballing. The continuous rotation of the vehicle will complicate docking and un-docking of secondary vehicles. Vehicles will be forced to approach the rotating ISV at the center of rotation and perhaps even attempt to match the ISV's rotational velocity. At this point the robotic arm system (described in earlier sections) will grapple the approaching vehicle. The robotic arm system could then very slowly, so as not to induce high loads, move the vehicle to the off-center docking ports at the service node.

Artificial gravity is an extremely useful asset in long duration space missions for preventing the onset of muscular atrophy as well as allowing normal plant growth. Although not explored here, it is the authors belief that the benefits of artificial gravity far outweigh the design and operational challenges.

Bio-regenerative Life Support

Bio-regenerative life support offers an extremely efficient system for producing food as well as recycling air, water, and human waste. It has been estimated that by producing 50% of the total crew calorie intake a bio-regenerative system can provide 100% of the air and water revitalization [Wheeler, R.M., 2003]. The ISV will carry a greenhouse and composter system similar to the Phil Sadler's (University of Arizona) lunar greenhouse design[Sadler etal., 2009, 2008, 2007, Patterson etal., 2009]. Sadler's design employs a multi-crop hydroponic greenhouse for the production biomass and cycling carbon dioxide into oxygen. The composter completes the cycle by accepting the biomass and human waste and producing carbon dioxide thru microbial respiration (see figure 15). This bio-regenerative system provides nearly closed loop ecological life support (CELSS)and requires only hydroponic salts, power, and a closed system of water and air.

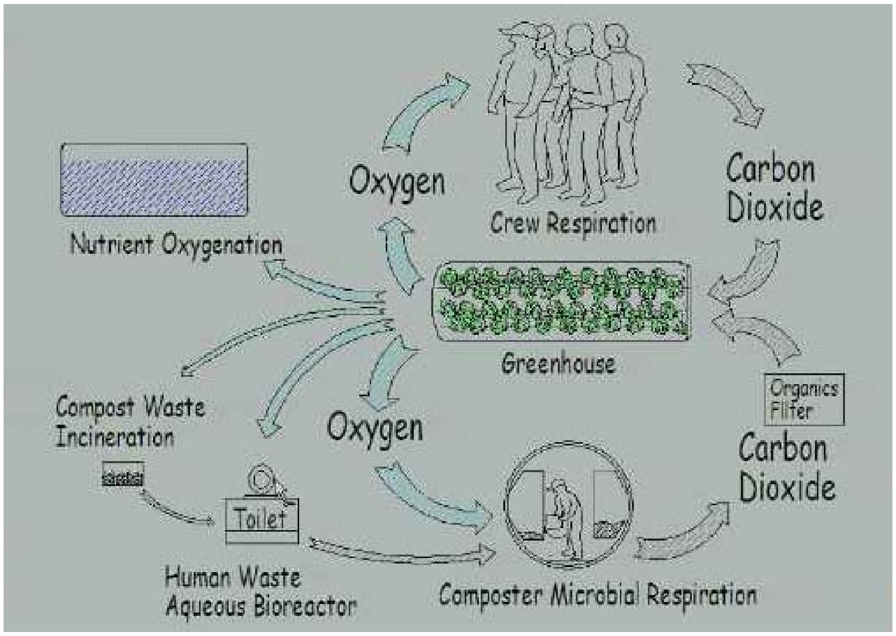

Figure 15: Atmosphere Revitalization Pathway

The greenhouse modules will be present within the TransHab modules of the ISV and can be certified during a test program of these modules on the ISS. The greenhouse modules, similar in design to the lunar greenhouse shown in figure 16, can be arranged within the TransHab to create an environmental room where crew can exercise, rest, and enjoy the presence of plant life. A similar concept was implemented by the Patterson and Sadler greenhouse design in the South Pole with very successful results on inhabitants' mental health [Patterson etal, 2008].

Figure 16: University of Arizona Prototype Lunar Greenhouse

Bio-regenerative life support systems have the compound benefits of recycling air, water and human waste as well as improving the living environment for crew members[Lobascio, C., etal., 2007] As mentioned in the earlier section on habitable volume, human factors are a critical consideration for long duration missions[Ball, J.R and Evans C.H., Jr.2001]. Bio-regenerative systems allow system designers to gain multiple utilities from one system.

Communications System

After crew safety and habitability are secured, the most critical system is communication. Loss of link is tantamount to loss of mission and therefore highly reliable systems are critical for the success of manned deep space missions. Communications platforms operating from extreme distances present special challenges. Since this is a multiple crewed mission, we can expect large data stream requirements[Hall, J.R., and Hastrup R.C., 1989]. Advanced optical communication technologies employing large bandwidths are proposed.[Gagliardi,R.M., Karp, S.,1995] Narrow beams require exceptionally narrow pointing tolerance[Boroson, D.M.etal 2003, 2004, Wilson,K.E and Lesh,J.R., 1993]. One way to achieve this is by using free flyer communications platform that fly in formation with the ISV[Aldrin,Thangavelu etal., 2002]. A free flying platform could be grappled by the robotic arm system and stored in the truss mounted containers during NTR burns.

ISV Assembly

The ISV must be built from the ISS using the ISS as umbilical. ISS would be the primary assembly platform from which robotic manipulation, EVAs, life support and power can all be provided. This eliminates the need for the ISV to be self- sufficient in the early stages of assembly and contributes to the efficiency of the fully assembled vehicle by removing many of the redundancy in the life support and power systems as is seen on the ISS Zarya-Zvezda (Functional Cargo/Service Block Modules). Many of the pioneered systems of the ISV, such as the TransHab inflatable modules, would gain the benefit of being certified at ISS before being fully commissioned in a mission. The ISS could will also get the opportunity to reach its full potential as a spaceport and spacecraft integration site.

Construction and certification of the ISV could require up to 10 years and would drive the development (or completion) of key space technologies such as nuclear thermal rocket technology, artificial gravity, space based greenhouses, and lightweight radiation shielding. Many of these technologies have previously been developed to high TRL levels of 5 to 7 as is the case with nuclear rockets and space based greenhouses. These programs can be restarted and pushed to completion by the ISV program in much the same way that liquid rocket propulsion and the Kalman filter were pushed by the Apollo program[Schmitt, S.F., 1980]

Assembling the ISV begins by docking the observation deck to the pressurized mating adapter 3 of the ISS as shown in figure 17. This location on ISS is within reach of the remote manipulator system (Canada Arm) as well as allows for vehicle growth during assembly. The ISS remote manipulator system will grapple and place the first elements of the ISV as well as provide EVA support until the ISV's robotic arm system can take over. From the observation deck, the remaining modules of the vehicle can be sequentially placed roughly following the sequence outlined in figure 18. A variety of traditional 5m fairing EELVs and Ares V class launch vehicles are required to place each module of the ISV into low earth orbit. Once in LEO each major component will need to be captured by a manned or un-manned transfer vehicle (not detailed here) to facilitate rendezvous with the ISS. Upon completion of assembly, test and certification of all ISV systems, the vehicle will be de-mated from the ISS adapter 3 and begin its first mission as shown in figure 19.

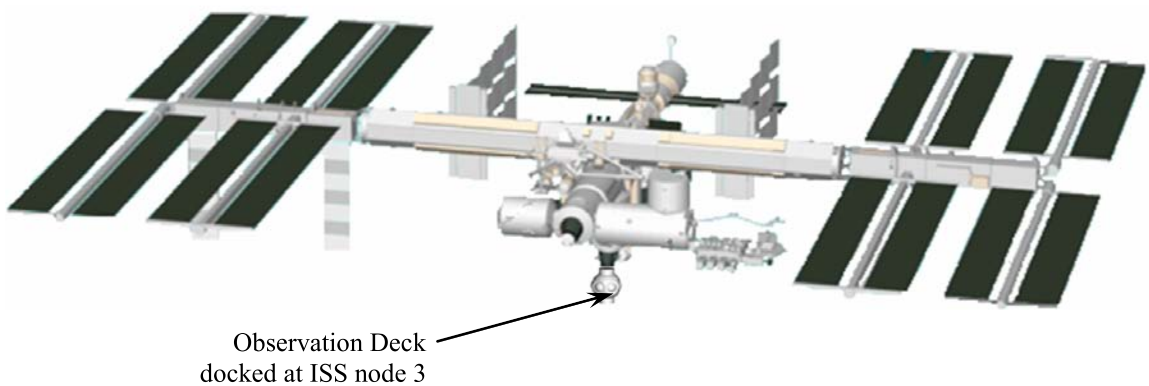

Figure 17: Primary Module Docked to ISS

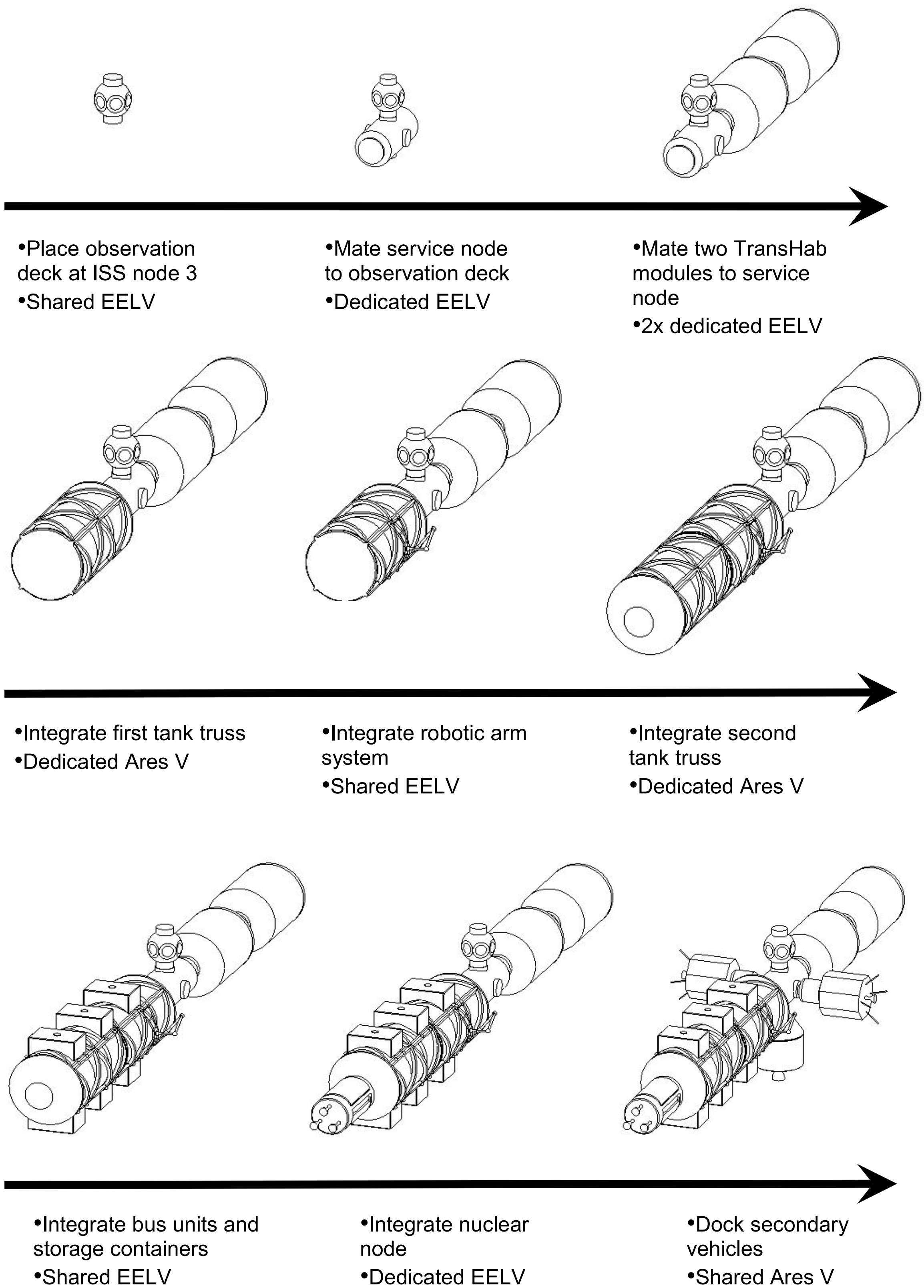

Figure 18: ISV Integration Build Flow

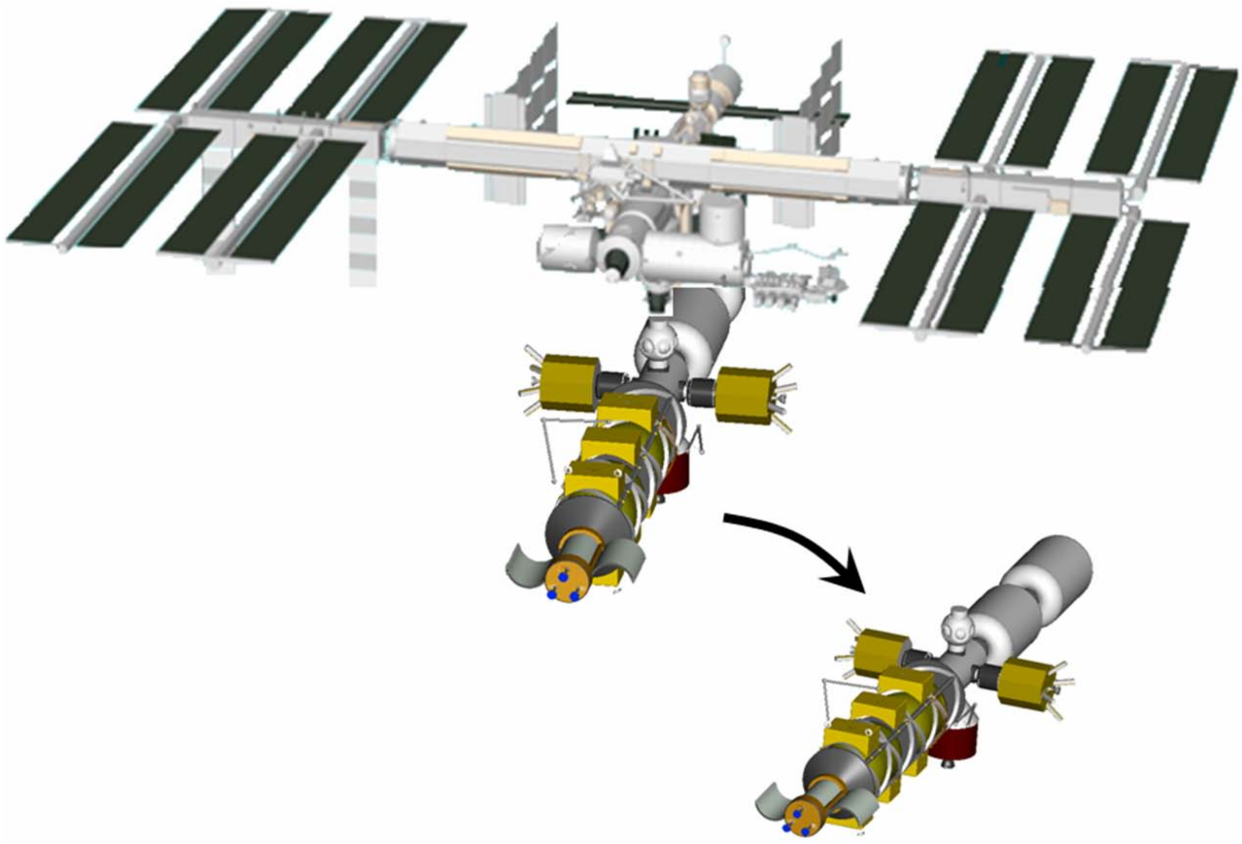

Figure 19: Complete ISV Undocked from ISS

III. ISV Utilization

Manned Missions

Once built, the ISV could be flown to the moon and used to support several long duration missions to the lunar surface. Use of the ISV's large fuel tanks and electrolysis center allows for refueling of lander vehicles for several journeys to the lunar surface. These missions would serve as a proving ground for an eventual trip to Mars (or other valuable NEOs). On these lunar missions, members of the international crew from partner nations could be the ones to spend time on the lunar surface. This will serve as an enormous incentive for nations to partner with the U.S. to build the ISV. The U.S. can still benefit from any discoveries made on the lunar surface while the national prestige of landing on the moon can be leveraged to forge solid partnerships.

After the ISV has been proven to operate as designed it could be used to take humans to Mars or Phobos. The reasons for travel to Mars and its moons will not be addressed in this paper however it should be stated that the ISV will support these missions in a much more robust way than an Orion capsule could. The utility of any mission to Mars will be far greater using an ISV or similar design.

Self Replication

The ISV can also serve as a space station in many of the same capacities as the ISS. It can provide the function of a safe haven or platform from which to conduct on orbit integration. The ISV can, perhaps most interestingly, be used to build another ISV or derivative. Derivative stations could be parked lunar or other orbits and serve as space ports for manned missions across the inner solar system[Thangavelu, 1989]. These spaceports could also be used to service high value assets in much the same way the shuttle maintained the Hubble Space Telescope. Implications of this self replicating capability should be considered with the long term initiatives of the world's space programs.

IV. Conclusion

The International Space Transit Vehicle(ISV) proposes a new approach to complex manned space vehicle design and commission. At the outset, three segments of space operations were clearly identified:

1. Earth to Orbit and Orbit to Earth segment
2. Earth Orbit to Destination Orbit or Space Transit segment
3. Extraterrestrial Operations segment

Each of these segments have very different environments and therefore, very different operational requirements. The ISV concept focused on the second segment, namely the Earth Orbit to Destination Orbit or Space Transit segment. It aims to employ the ISS and her crew as a manned assembly node, integrating the entire space transit vehicle stack and performing checkout operations while still docked to the ISS. The ISS crew, with a substantial heritage of assembly of modular components for the ISS, will use similar components and systems to build and commission the ISV.

The resulting large vehicle stack is meant for transiting crew, initially in cislunar space between Earth and lunar orbits, and eventually for interplanetary missions. At the origin and destination orbits, other attached shuttles and landers are employed to ferry crew. In this way, the system is optimized for the specific function of inter-orbital expeditions.

The ISV is not designed to accommodate large loads associated with maneuvers like aerobraking or high thrust translunar or interplanetary injection. Thermonuclear propulsion allows for variable specific impulse and a high degree of throttleability. Using spiraling trajectory optimization, the stack employs nuclear power to thrust the vehicle gradually into the desired trajectory.

The salient features of this international craft and mission are :

1) It uses bimodal nuclear thermal rocket technology for propulsion and power needs.
2) It carries water that is converted by electrolysis as needed into fuel. Such a strategy drastically reduces tankage and cryogenic systems associated with boil-off. A water jacket also provides an effective radiation shield and solar storm shelter for the crew on endurance-class missions.
3) It provides artificial gravity by rotating the entire, rigid vehicle stack.
4) A free-flying high bandwidth communication system is proposed to provide a vibration-free platform that is necessary for accurate pointing from extreme mission distances.
5) A closed bio-regenerative life support system is preferred to reduce the complexity of the physical plant associated with air revitalization, water recycling, food generation and waste management.
6) It supports six crew of international makeup, and the proposed habitable volumes are larger than those in the Mars500 mission that is in progress now[ESA, 2010].
7) Uses existing and evolving ISS components and logistics support for building the stack.
8) The first orbital cycling missions are planned between the Earth and the Moon. Eventually, the stack is evolved to support interplanetary transits.
9) This project is seen as the next step in evolving the international partnerships to include more nations into the current successful ISS model for the peaceful uses of outer space.
10) It follows the President's space policy that is derived from recommendations made by the Augustine Committee.[The Whitehouse, 2010]

Large risks to this program are present in the incorporation of very aggressive technologies in the design. The previously identified technologies will require large investments of financial and human capital as well as the build up of infrastructure in the U.S. and around the world. Although many of these “next generation” space technologies are presently at high TRL levels, the authors recognize the larger risks involved when incorporating new technologies into production programs.

The ISV will require significant servicing and refurbishment in between missions which will draw out the time between missions. This may or may not present challenges depending on the target missions and orbital opportunities.

The ISV can not be mass produced in the near term and will therefore be one of a kind. This means that only one mission can be accomplished at a time and it also represents a single point failure. Should the ISV catastrophically fail, it will set the space exploration program back several years in much the same way as the space shuttle disasters.

Building the ISV will take a long time as identified in the assembly sequence section of this paper. This will require the ISS to support the ISV assembly and will decrease the availability of ISS resources for research and other missions. This opportunity cost is unavoidable since the ISS is the only platform that can support the complex ISV assembly, certification and commission.

Healthy international collaboration in the existing ISS international model is a prerequisite for starting the ISV project. Opening up dialog with more international partners and even commercial entities playing a large role is required well in advance of starting the ISV project. The project can also be affected by international conflicts of interest and disputes, and changes in the governmental policy of partner nations, much like the ISS.

As mentioned previously, the ISV delivers much higher mission utility for any given mission to another celestial body. Its ability to remain at that body for long durations allows astronauts to conduct many more mission objectives as well as provides more options and time to resolve anomalies. The ISV will support long term missions to the Moon, various near earth objects, and Mars. While on these missions, mankind will learn not just how to arrive, set foot and leave an extraterrestrial body but instead how to survive and thrive enroute as well as at that destination body.

The ISV program will advance and drive key space exploration technologies to operational levels. Because of the incorporation of artificial gravity, bio-regenrative life support and nuclear rockets in the design of ISV, all of these technologies will be developed and available for use in other programs. The ISV program will drive international investment in the development of all of these systems in much the same way the Apollo program advanced U.S. investment in rocket technology, guidance, navigation and control systems and space suit life support. This also presents an opportunity to drive global private sector investment in technology development on order to win the contracts associated with all of the many ISV subsystems.

The offer of international crew members descending to the moon will create enthusiastic international support for the ISV program. One need only observe the merits of international collaboration in the ISS program to imagine the huge opportunities created by a multinational effort to build the ISV.

Finally it is the hope of the authors that the ISV can inspire the children and a new generation of explorers everywhere in the same way that Apollo captured the world's imagination.

Acknowledgements

This project is part of the Fall of 2009 team project entitled:"The International Space Station: Investing In Humanity's Future" in the ASTE527 Graduate Space Exploration Architecture Concept Synthesis Studio, an elective offered in the Department of Astronautical Engineering within the Viterbi School of Engineering at the University of Southern California. The course is all about the creation of innovative ideas and applications of human space activity. We were tasked with looking at alternative futures for the ISS, and the entire set of team project slides may be found at : http://denecs.usc.edu/hosted/ASTE/TeamProject20093/

Daniel Roukos would like to thank the USC Department of Astronautical Engineering faculty and his mentors at the Boeing Satellite Development Center for sharing their unique knowledge of space vehicle engineering and their guidance through the complex and forever fascinating field of Astronautics.

Appendix

Component	QTY	Mass (kg)	Sub (kg)	Total
Trans Hab	2	13200	26400	
Service Module	1	17200	17200	
Observation Deck	1	4000	4000	
Primary truss/tank (dry)	2	15000	30000	
Nuclear Node	1	20000	20000	
Crew Transfer Capsule	1	25000	25000	
Lander Vehicle	2	45000	90000	
		Total (kg)	**212600**	

Figure 20: ISV Dry Mass Estimate

List of Volumes	QTY	Volume (m^3)
Trans Hab	2	342
Service Node	1	117
Observation Deck	1	34
Crew Capsule	1	15
Altair Lander	2	32
	Total (m^3)	**914**

Figure 21: Pressurized Volumes

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