AAE 450, Spring 2015
Spacecraft Design

Specifications for Project Aldrin-Purdue

Dr. Aldrin's book, *Mission to Mars: My Vision for Space Exploration* lays out a wide range of goals that, step by step, will lead to “commencing American permanence on the planet Mars.” The class will expand that concept to include international presence of Mars.

Professor Longuski's Spacecraft Design class will assess some of the challenges presented by Dr. Aldrin, and further refine the basic concepts. The class consists of about 50 seniors who will work together as a team to flesh out the details involving the following disciplines:

1. Aerodynamics (aeroshell, aerocapture, aerobraking, entry, descent, and landing, etc.)
2. Attitude Control (actuators, sensors, pointing accuracy, propellant budget, etc.)
3. Communications (antenna, link budget, etc.)
4. Mission Design (trajectory, navigation, launch vehicle, etc.)

5. Power and Thermal Control (solar, nuclear, batteries, etc.)
6. Propulsion (engines, attitude thrusters, propellants, etc.)
7. Human Factors (radiation, consumables, life support, etc.) and Science
8. Structures (materials, mass properties, etc.)
9. Cost, Schedule, Surface Operations, and Risk Assessment

These specifications are derived from three primary sources: 1) Dr. Aldrin's book, *Mission to Mars*, 2) “The Executive Summary of Buzz Aldrin's Vision for Space Pioneering Exploration” (by Aldrin, B., Mihaly, J., Rosen, S., and Battat, J.), and 3) personal communications with Dr. Aldrin on Oct. 30-31, 2014 when he visited Purdue.

The specifications for Project Aldrin-Purdue are as follows.

Project Aldrin-Purdue Specifications

Overall Objective:

Minimize the IMLEO of establishing and sustaining a permanent human presence on Mars by 2040, consistent with the following specifications. (Note that initial mass in LEO, i.e. IMLEO, is closely related to the cost. Also, a reasonable cap on annual spending should be considered.)

Detailed Requirements:

Appropriate launch vehicles should be selected to serve the project. The usefulness of the SLS should be considered and compared (traded) with other existing or reconfigured options. Integration with other space transportation architecture elements should also be considered (e.g. lunar fuel production and in-space fuel depots). Since these transportation elements may be established for other purposes.

Development and operation of these elements may or may not be accounted for in total mission costs—various cases should be assessed.

As required by Aldrin, the project can begin as soon as 2022 with the launch of inflatable 1st generation exploration modules (XM1), the Bigelow BA 330, which may be flown to

- LEO
- L1 to support lunar nearside activities
- L2 to support lunar far side activities
- To an asteroid in combination with robotic explorers

A communication relay network from Earth to L2 should be established using one or more of the following options:

- an L2-Halo
- a low-lunar orbit
- a Lunar Distant Retrograde Orbit (LDRO)
- an elliptical Lunar Distant High Earth Orbit (LDHEO)

As required by Aldrin, the purpose of these flights is to test exploration modules, to provide locations from which to remotely construct an international lunar base, and to initiate human-assisted in situ asteroid exploration and development. These lunar activities will provide the necessary experience to remotely construct (from Phobos) the base on Mars.

The international lunar bases are constructed via tele-operations from L1 for a near-side base (and from L2 for a far-side base). Each lunar base consists of a core of three 2nd generation exploration/habitation modules (XM2), possibly using rigid structures from the European Space Agency (ESA) or a consortium of international partners. In addition to providing lunar bases, these activities serve to test concepts, hardware, and procedures to be used at Mars, such as overall base assembly and checkout (including placement and interconnection of the modules on the surface). They also provide the basis for extended lunar operations, including resource extraction, as well as a capability for future human missions to asteroids.

Three lunar bases consisting of three connected XM2s should be constructed. Two bases should be placed with one each on the near and far side of the moon. Additionally, one lunar base should be located near Shackleton crater so that ice can be harvested for propellant to support (1) the establishment, and station-keeping of the cyclers (2) operation of LEO-to-cycler vehicles, and (3) other possible scenarios. The effectiveness of using lunar in situ propellant should be compared with propellant that originates at Earth. The preferred location of a refueling depot (if needed) should be established, either in Earth orbit or at lunar distances.

Astronaut crews travel to Mars on a cycler vehicle, on a trajectory known as S1L1. (See McConaghy, T. T., Longuski, J. M., and Byrnes, D. V., "Analysis of a Class of Earth-Mars Cycler Trajectories," *Journal of Spacecraft and Rockets*, Vol. 41, No. 4, July-August 2004, pp. 622—628.)

The *cycler schedule* is as follows

1. Beginning in 2028 (before the first cycler is sent to Mars) and by 2034—nine unoccupied exploration modules, XM3 (“habs”, based on XM2 exploration modules) should be launched to Mars and two habs on Phobos. To keep propellant mass low, habs will be delivered to Mars using low-energy cargo trajectories (e.g. Hohmann or low-thrust transfers including the ballistic capture technique of Belbruno and Topputo). Phobos-to-Mars telerobotics will bring the XM3s as close as possible together at the selected and prepared location. All interplanetary launches (including both cargo and cycler) should include a trajectory correction maneuver (TCM) budget of 100 m/s per synodic period.

2. The first cycler, Cycler A, carries three landers with a total of six crew members. One unmanned lander lands on Mars to demonstrate and checkout Mars landing procedures, and two landers land on Phobos with six crew members. Alternatively, these landers may be delivered to Phobos via Cargo trajectories. The Phobos crew will conduct remote exploration of the Martian surface and atmosphere, and will remotely prepare the Mars surface site for habitation, using techniques developed at the Earth-Moon libration facilities. This crew may then transfer to the Mars surface.

3. The second cycler, Cycle B, carries three landers with a total of

18 crew members. One lander with six crew members replaces the original six crew members on Phobos. The remaining two landers land on Mars with a total of 12 crew members. At this point there are 18 crew members on the surface of Mars with four landers, and the first permanent settlement on Mars is established. As required by Aldrin, for the foreseeable future the Phobos base will always be occupied by six crew members, but not for more than two years for any crew member.

4. Each synodic period afterwards will deliver another 18 crew members until the expansion of the Mars colony via transport of humans is no longer necessary, since the colony can sustain itself. The Phobos crews and the growing colony on Mars will live and work in habs delivered by cargo vehicles using low-energy transfers. Cargo vehicles must take less than one synodic period (2 1/7 years) to reach Mars, unless longer trips can significantly reduce mission cost and risks. Cargo vehicles will resupply the colonists with consumables (food, water, and oxygen as necessary) and replacement hardware.

Continued support of the colony through Earth supplies will still be necessary for an undetermined period in the future. The architecture for conducting resupply missions should be investigated. It is expected that replacement equipment, repairs, maintenance are important IMLEO drivers.

In situ resource utilization (ISRU) on Mars should be considered (e.g. to produce water, oxygen, and propellants) in order to reduce the number of cargo resupply missions. The impact of growing food on Mars (after the establishment of permanent human presence on Mars in 2040) should be assessed.

Each of the cycler vehicles consists of three XM3s which would be similar to the XM2s on the Moon, and XM3s on Phobos, and Mars with the exception that the surface XMs have leveling legs. Each XM can house a crew of six (for a total of 18 people on each cycler vehicle).

Radiation shielding (with areal density of 100 g/cm^2) should be provided whenever a crew is on a surface hab on the Moon, Phobos, or Mars (We note that this value amounts to a shield of 1 metric ton per square meter which is equivalent to a shield thickness of 1 meter of water.). See the National Research Council's report on radiation protection requirements ("Space Radiation Hazards and the Vision for Space Exploration: Report of a Workshop," National Research Council, National Academies Press, Washington, DC, 2006). During interplanetary flight (such as on the cycler) minimal radiation shielding should be employed (in order to minimize IMLEO). Rovers will carry no additional shielding.

Although the cycler vehicle should be as “low-mass” as possible, it is more tolerant to mass growth than a direct single-mission vehicle. Because it is reused, there is an accumulating mass savings in every re-use regardless of how much shielding is employed. (If heavy shielding is found to be necessary, the advantage of the cycler concept becomes far greater than a direct single-use approach.)

Artificial gravity on the cyclers is not required. However, the option of providing artificial gravity should be investigated. Artificial gravity is required for crews while on the surface of Phobos. A short-radius centrifuge may be used. The centrifuge should provide the Phobos crew with a 0.38 g artificial gravity field to allow for using a toilet and shower, as well as for exercise. All members of the Phobos crew will use the facility for about one hour per day. Two artificial-gravity devices should be provided.

Operations on Mars involve joining nine modules (XMs) together (e.g. three in the center and six on the outside) on the flattest possible location (which won't be perfectly level). The modules are connected by either circular or square tunnels. The modules will be the same design as the ones on the cycler (and could be inflatable). For example, a flatbed crane may be used for the purpose of joining the modules. Habs (XMs) will be placed on the Mars surface with the axis of the cylinder perpendicular to the surface. Each module may have several parallel internal floors.

A site suitable for the Mars colony should be determined. (A possible candidate is the Gale crater.)

The landing errors on Mars (for both XMs and landers) are assumed to be less than 6 km (with a probability of 99%). During landing cargo on any surface (i.e. the Moon, Phobos, or Mars), the vehicles should have the capability of hovering for at least 30 seconds. Landers with colonists on any surface should have a 60-second hover capability.

Landers should be convertible (or transformable) to pressurized rovers, useful hardware, etc. Reconfigurabilty, commonality, and reusability of key equipment should be a guiding principle. For example, the flatbed crane for placing habs, the construction equipment for leveling the base surface, and the pressurized landers should all share (to the degree possible) a common chassis design.

Transformable landers can be attached to the connected hab modules to provide additional living/working volume.

The crew should always operate in a shirt-sleeve environment. Spacesuits should only be used as a safety precaution; exploration should be conducted primarily in pressurized rovers. (See Mary Roach's *Packing for Mars: The Curious Science of Life in the Void*, W.W. Norton & Company, New York, NY, 2010. where she explains the advantages of exploring in a pressurized rover, rather than in “bulky, uncomfortable white bubble-head EVA suits” on pages 175-176 and why as one spacesuit historian said on page 263, “It's not a nice place to be. It's not even a nice place to visit.”)

All rovers will be pressurized and occupied by humans. These rovers should have science instruments similar to the Mars Exploration Rovers (MER A and MER B), the Mars Science Laboratory (MSL) rover, and the planned Mars 2020 rover. They should be equipped with sufficient lights, stereoscopic cameras, microscopes, telescopes, and geologists' tools. They should have an array of actuators (robotic fingers, hands, arms) that can pick up a dime or lift bigger objects. Rovers should be faster, safer, stronger, and more dexterous than crew members in space suits. (Again, extra-vehicular activity will only be used during emergencies).

Pressurized rovers should be able to travel a round trip distance of 200 km at a speed of 20 km/h up an incline of 30 degrees. They should have airlocks compatible with each other and with the habs. They should have the nominal capacity of three crew members and be able to accommodate a total of six crew members during emergency. For operations on surface the Moon and Mars, there will be at least one rover provided for every six crew members. The rovers will have no radiation protection.

The first Phobos crew of six from Cycler A descends to Mars just before two landers from Cycler B. At this point, there will be a total of 18 astronauts on Mars and a crew of six on Phobos (See items #2 & #3 of the *cycler schedule*). (The use of Phobos as a further exploration location is specified by Aldrin.) Thus, there will be four landers on the surface of Mars and two landers parked on the surface of Phobos. (Note that all landers can be transformed to rovers on Mars.) For three days a week rover pairs will explore Mars on round trips of up to 200 km. For example, Rover A and

Rover B will travel together on Monday, Wednesday, and Friday and Rover C and Rover D will travel on Tuesday, Thursday, and Saturday. All rovers will rest on Sunday. Similarly once the lunar colony has expanded to 24 crew members, lunar rovers will follow the same schedule.

The Phobos crew of six should be able to return to the Earth using a lander and an inflatable hab with trans-Earth propulsion to provide a first-mission-return scenario. An extreme abort option from the surface of Mars should be provided to return up to three crew members to Phobos and then to the Earth. In this abort option, a cycler vehicle will not be used (due to the long return leg of the outbound S1L1 cycler). It is expected that storable and/or solid propulsion is necessary for Mars-to-Phobos, and for Phobos-to-Earth transfers.

Continuous (uninterrupted) two-way HD video is required between each of the astronauts and Earth, during all phases of the mission. (This communication system may provide a commercial service opportunity.)

Pressurized rovers are required for exploration on Mars. Robots may be used to assist exploration.

On taxi flights from LEO outbound to Mars, precautions must be taken to minimize the risks involved during hyperbolic rendezvous with the cycler vehicle. Hyperbolic rendezvous is a very time-critical maneuver requiring a high degree of targeting accuracy. Yet, for all architectures, once trans-Mars ignition (TMI) is reached, propulsion failures in the last 20% must be protected by redundancy.

Cost for lunar and Mars operations and the lunar and Mars bases should be funded by international partners working with the United States.

The probability of safe return of astronauts on voyages to the Moon and to an asteroid should exceed 95% (for each mission).

The probability of safely landing astronauts on Phobos and on Mars should also exceed 95% for each mission.

The design ends when sustained human exploration of Mars commences in 2040.

End Project Specifications

These project specifications are subject to change at the discretion of the customer (Dr. Buzz Aldrin).

NOTES ON COST: Cost analyses (which begin with IMLEO assessments) should include several breakdowns including the cost of (a) early generation one (XM1) missions; (b) lunar base; (c) annual lunar base operations; (d) placement of cycler vehicles; (e) first human mission to Phobos; (f) second crew to Mars; (g) annual resupply and operations of 18 colonists on Mars and six colonists on Phobos; (h) second wave of colonists to Mars; and (i) annual supply cost of 36-person colony and six-person colony on Phobos. A cost comparison using a direct mission to Mars, i.e. without the cycler transportation system (which includes three landers per synodic period) should be made. It is expected that the sustaining cost for such colonies on Mars will be more for the direct approach compared to the cycler approach due to the fact that the cycler vehicle interplanetary XMs will be reused whereas in the direct approach, a large recurring cost results for the each new interplanetary hab. It should be noted that the design of the cycler hab will be such as to minimize the mass of the cycler vehicle so that it is similar in mass per person to that of the hab used in the direct approach. The cost for a crew of three instead of six per lander should be estimated.

NOTES ON RISK ASSESSMENT: It is important to assess risks and relative risks of different approaches. For e.g. launch vehicle capability affects on-orbit assembly risk, launch availability, and cost associated with different launch vehicle production.

ADD NEW SPECIFICATIONS HERE

1-27-15: The three (human) landers should be assembled in LEO and rendezvous with the Cylers (A or B) using hyperbolic rendezvous. The system should have a triple redundancy as required by Dr. Aldrin. The option of separately launching the landers to a Cycler should also be investigated.