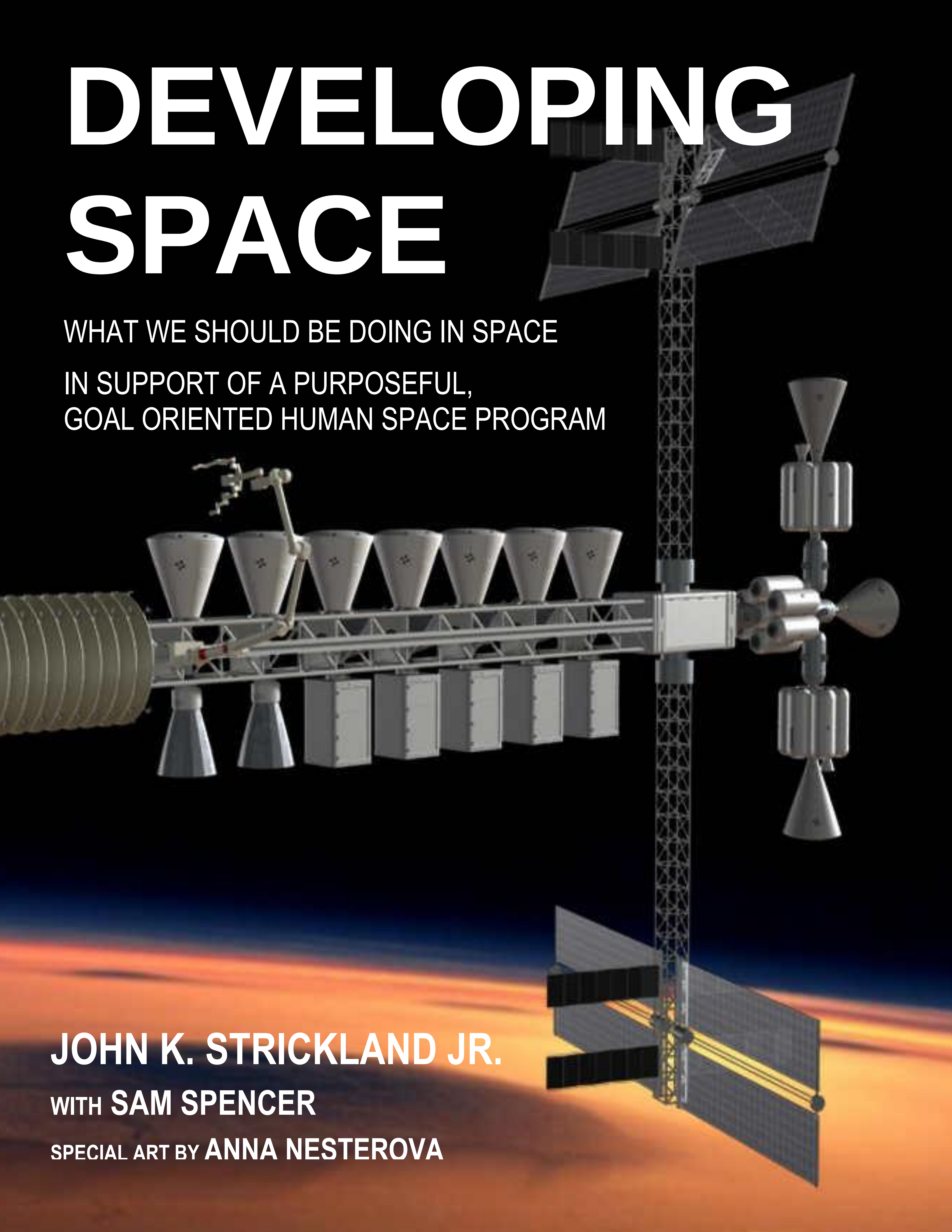
DEVELOPING SPACE

WHAT WE SHOULD BE DOING IN SPACE

IN SUPPORT OF A PURPOSEFUL,
GOAL ORIENTED HUMAN SPACE PROGRAM



JOHN K. STRICKLAND JR.

WITH **SAM SPENCER**

SPECIAL ART BY **ANNA NESTEROVA**

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F. The Mars Science Base

This section will outlie the layout, power sources, radiation protection, habitats, food production and operations of a potential Mars Science Base.

F.1 General principles for Mars base layout.

A primary requirement for a base is a generally level area that is large enough for all of the bases installations, and with a layer of regolith deep enough to excavate at least 5 meters down and bury multiple habitat modules. The landing and takeoff areas should be at least 1 km away from the base to prevent damage to habitats and infrastructure during landings and takeoffs caused by flying gravel and also to prevent pieces from a failed entry vehicle from impacting in the base area. As orbital paths will generally be in a west to east direction, the base should be laid out along a north-south road with all entry ground tracks kept well away from overflying the base area. As vehicles entering from orbit approach the base area, the ground track should be aimed to pass well north or south of the area. Just before landing, the flight paths would be changed to aim directly at the specific designated landing pad area. Each pad area would have its own local beacon and local Mars GPS signal.

All utilities such as electrical cables and pipes should be buried to protect them from damage from vehicles, foot traffic and thermal extremes. This means a trenching machine is needed. The propellant plant should be within power cable range of the base, but on the side towards the ice deposit. The power plant should be at the edge of the base with ample room for at least 30 megawatts of radiators. Room should be provided for future expansion of the major base components and habitats. The propellant depot (fuel storage) should be close to the propellant plant to allow easy transfer of fuel to the depot. More than one source of power is needed, such as nuclear and solar, along with a large battery or fuel cell backup system. A road network (other than the main north-south road) should be established to link launch site, work areas, habitats, fuel production, fuel storage and other areas. Surfacing for the road would probably not be required. Large Quonset shells, which can be packaged densely for shipping, would be needed to protect outdoor vehicles and equipment from Mars dust and low night temperatures as heat radiates into space.

F.2 Power Sources

The overriding first objective, before any crew arrives, is a power source; which is needed to produce propellant for the ferries. Once a base site has been picked, fuel producing equipment would be among the very first payloads sent down to the surface by cargo ferries. The integrated transport system is not complete until fuel production begins. The equipment could be offloaded and set up via tele-operations by crew in LMO. Until that happens, the initial set of cargo ferries to land would accumulate at the base landing zone, protected by design from low Martian temperatures and dust. All of the equipment sent to the surface, including the cargo ferries, needs to be designed to withstand the cold temperature extremes at the surface. Radio-isotope heat sources may need to be used to keep specific areas of the equipment and vehicles above specified temperature limits.

This initial work without the crew requires excavators, ditching machines, work robots, small nuclear reactors, cable, the components of the propellant package plant and at least part of the propellant depot with tanks. Staging the sequence of cargos to be landed during the bootstrapping sequence would be critical to success. Among the very first items would be one or more mobile tele-manipulator robots, along with a crane on wheels which the robots could assemble, or a flatbed truck with a winch. The robots could also assemble a platform and ramp to offload initial cargo from the Ferry's cargo bay. The crane or truck would allow removing items from the cargo bay directly, by first sliding them horizontally out of the bay onto the platform or truck flatbed with the winch and then moving them away from the designated landing zone. The other high priority initial "bootstrapping" items would include a flatbed truck, an excavator, the propellant production plant, a reactor, a tanker (fuel) truck and a set of insulated tanks with cryo-coolers to store the propellant.

It should be underscored that power sources for humans on Mars are essentially non-existent, so we must import or build them. Solar power will probably be used, but it is very bulky and labor-intensive to install. In the future, until fusion power succeeds, Mars cities will almost certainly rely on space solar power, if they want to be resource-independent of Earth. However, for the near term, Mars bases will almost certainly rely for a major part of their power on small, sealed nuclear reactors, which would probably last 15 years before needing to be replaced.

A set of at least 3 reactors (depending on the actual power output) each about 1-cubic meters in size, would be buried in the same area near the base site, with surface power equipment mounted nearby. Power cables would be laid in trenches to take the power over to the fuel production plant and later to power the base. With the smaller reactors a total output of about 9 megawatts of thermal reactor heat from 3 reactors will be needed to produce 2.25 megawatts of power, and 6.75 megawatts of waste heat; which must be dispersed by radiators arrayed on the surface. This provides 50 kilowatts of power for the base and 2.2 megawatts for fuel production. The radiator array would be set up and the fuel package plant would be assembled by robots, all under the supervision of the crew in orbit.

The current reactor design described above is based on a paper created by a Texas A&M student project (Carasik, 2015). More information on this general type of reactor can be seen in Section VII.F in Chapter 2 of **Settling Space**. These are small, compact, sealed reactors that need no servicing. The reactors can be sized to fit the size of the available transport. The current design needs a total of about 10 metric tons of mass for each megawatt of electric power, of which 1 ton is the sealed reactor core itself. The other major components such as the generator-turbine, the radiators, the heat exchanger, the plumbing and structure etc., probably each have a mass between 1- 1.5 metric tons. This means that a total of at least 30 metric tons is needed for the reactor set, which would be brought down initially in 3 separate ferries.

If we use all 7 cargo ferries, the reactors would use up about 40% of each of the 3 full ferry loads, leaving 4 full ferry loads and 3 partial loads to bring down the tanker truck, crane or unloader, excavator, assembler robots and the parts for the fuel production plant. Once the reactors and fuel plant were running, the next set of cargo ferry loads would habitat modules and supplies for the crew. *S*ince the total cargo mass is about 625 tons, the total number of reactors could also be increased to speed up the frequency of trips during the second phase of ferry operations – after the crew arrives.

The A&M reactor design uses a Brayton (closed) cycle heat engine system to produce power through a turbine and generator. The reactor core is only about 1 cubic meter in size and is cooled by a mixture of liquid Sodium and Potassium. The reactor does not use water or steam to operate the turbines to prevent accidental mixing of the sodium and water. Instead, a heat exchanger transfers the heat to a working fluid composed of helium and xenon, which do not become radioactive and does not react with the liquid metal. The hot gas under pressure spins the turbine in the surface generating plant, producing power. To create a better temperature differential, the lower pressure and lower temperature gas is fed through a second heat exchanger which connects with the large surface radiator array. The fluid in the radiator is probably at an even lower pressure to prevent leaks in the radiator surfaces. Since the working fluid is a gas, it is not subject to freezing at Mars temperatures, unlike water cooled engines. Since the air on Mars is 100 times thinner than Earth air, there is less heat transfer by convection from the radiators, so some of the heat is dispersed directly by infra-red radiation. The lower temperature gas is then re-pressurized by a compressor and pumped back underground to the heat exchanger to be re-heated.

A NASA sponsored paper from 1988 (Wetch, 1988), covers Brayton cycle reactors intended for use in space where there is no air, so all of the heat must radiate. The reactors described are similar in size to the A&M reactor, but slightly less efficient, at about 20%, and it needed only 185 meters sq of surface area per Megawatt for a total of 1850 m^2 for a 10 MW output reactor. This indicates that a reactor system for a 10 MW_e Mars base design would need less than 2000 square meters, and a 3 MW_e would only need about 600 m^2. The larger radiator could be based on radiator surfaces that were set on A-frames at 45 degrees, with a 2.5-meter-wide radiator surface on each side, for a total A-frame length of 400 meters, or 8 rows of 50 meters long. The reactor, turbine and radiator design needs to take into account the probable need for robotic assembly and set-up of the whole system.

During the night or rare heavy dust storms, the vehicles used for the ice mining operation would be parked under Quonset shells, which can be assembled quickly from short curved segments. The excavators would then remove any regolith from on top of the ice layer at the ice mine, near the base site, and then start removing the ice. The ice may be very hard like rock, so that it may need to be ground away with a machine similar to a coal mining excavator. The ice (with some soil) would then be carried over to the propellant plant and dumped into the hopper. Once the hopper is pressurized with CO2, the ice is melted and filtered. It may also be put through a deionizer and probably through reverse osmosis filters. The correct electrolytes are then added to the pure water, which is then electrolyzed into hydrogen and oxygen gas. Each section of the package plant does a different step of the process. This process is covered in the previous chapter in great detail. The gases are then liquefied to cryogenic temperatures and pumped through insulated pipes into the propellant depot’s tanks. The depot would be completely covered with a shed to prevent sunlight from hitting the tanks, and it would have a set of fuel hydrants to allow insulated tanker trucks to move different kinds of propellant to the launch site.

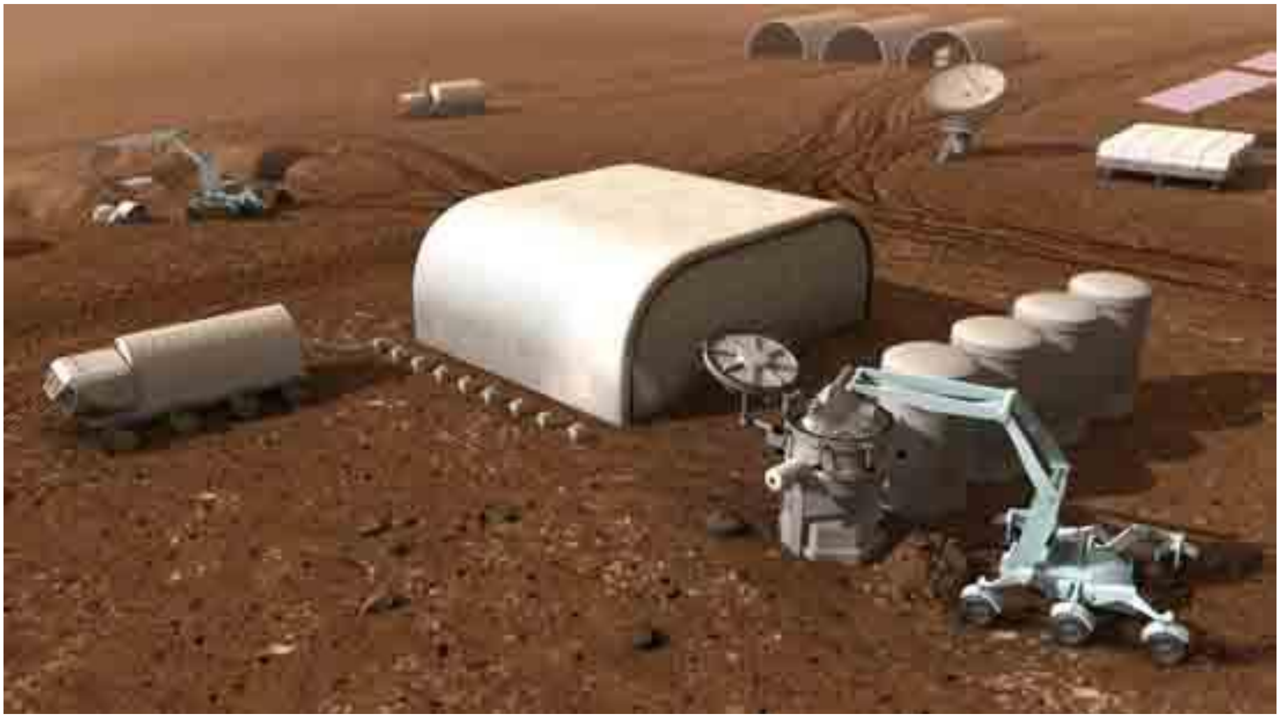

Figure 9.13: Mars Science Base Fuel Production and Fuel Depot area [Anna Nesterova]

With propellant production underway, the cargo ferries could be re-fueled via tanker and take off for the Low Mars Orbit base. This makes a good case for keeping the crew in Mars Orbit until propellant production was assured and would allow buildup of a large propellant supply on the surface *before* crew arrival. The robots would assemble the fuel production components next to the base habitat site and near the ice deposit and production would be started with crew members operating the robots from orbit. The initial set of cargo ferries would be forced to wait on the surface until sufficient propellant was generated, and then they would be re-fueled one at a time and take off for Mars orbit to bring down crew habitats and other equipment for use by the crew. One obvious problem is the balloon cargo of bringing empty propellant storage tanks to the surface. If instead, the ferries themselves were insulated and provided with a source of power near the launch and landing site, the propellant could be stored in the ferries themselves, removing a major logistics problem. A cargo ferry could then take off as soon as it had enough propellant loaded. The next load or two would probably be more reactor components, but later, crew habitats. At some point, the first crew members would ride a crew ferry down to the surface base, becoming the first humans to set foot on Mars.

F.3 Radiation Protection for Mars Surface Habitats and crew

Since burying the reactors works well at trapping any of their radiation, the crew can spend most of its time indoors, where they will be protected from the great bulk of cosmic radiation most of the time, since the habitats also need to be buried. Moses and Bushnell point out that the expensive surface habitats offer little protection against the 37% of Galactic Cosmic Radiation (GCR) that exists on the surface. (Moses & Bushnell, 2016). We can estimate the surface radiation result from the interplanetary value of about 657 milliSieverts (Perrotto & Schmid, 2013), (an appropriate unit of measure for biological radiation dose). A NASA release reveals that Curiosity got an average of “1.8 milliSieverts of GCR per day on its journey to Mars” which works out to 657 mSv/year. If we assume that Mars blocks half of it, we are left with 323.5 mSv, the dose level that probably exists in very low Mars orbit just above the atmosphere. The thin atmosphere of Mars then blocks more than 20 % of the remaining radiation, leaving a rate of about 255.7 mSv at the surface, the same as about 0.7 mSv per day (NASA/GFSC, 2013)**.** A similar effect works for the GCR radiation, assuming a 100 % interplanetary dose rate, a roughly 50% rate just above the atmosphere, (328 mSv/yr) and the 37% value given by the Moses paper, which is 0.37 * 657 = 243 mSv/yr, means that the atmosphere blocks about 26% of the estimated GCR component (243/328 = 74% remains).

Note that a crew does not necessarily need the same level of radiation protection as a civilian population, but if the regolith is available, why not use it. This would allow the crew more time outdoors, where they would have little shielding. Table 9.1 show the protection level afforded by several meters of water or Mars regolith. Here Mars regolith is assumed to have a specific gravity or density of 2.00 metric tons per cubic meter, about twice as dense as water. The basis of for this is that the density of crushed basalt (one of the most common regolith components) is at about 2 metric tons per cubic meter (Walker R. , 2016). We can assume that other lighter materials are mixed with the most common component, but that fine material will be filling the spaces between the pieces of basalt, so these two conditions may cancel each other out. Sand and dust in a thin layer right at the surface may be as low as 1.5 metric tons per cubic meter.

General sources indicate that radiation levels of 20 mSv are safe for civilian populations, but for pregnant women and children, the rate should be down to about 5-6. The average mSv level in the USA from background radiation is about 3, of which only about 1/10 is from cosmic radiation. Notice how the first meter of shielding blocks much more radiation exposure (57% blocked, 43% left) than the following meter (26% blocked, 74% left). This is probably due to absorption of the solar radiation component. The apparent lower blocking by the second meter may be due to production of lower energy secondary particulate radiation. After this the blocking rate the blocking factor gradually increases to about 38%. Most of the decrement ratio values for this table were compiled by Al Globus (Globus, Covey, & Faber, Space Settlement: An Easier Way, 2016) using the Oltaris Software. Each step shows the successive reduction to the next remaining dose value.

Table 9.1: Mars Surface Radiation Shielding Protection

Meters of Water (1 metric ton per cubic meter density)	Equivalent meters of Regolith to equal each meter of water	Blocking % - amount of dose BLOCKED by each layer	Reduction Factor (% of remaining dose)	Radiation (mSv/year) received below each layer
0	0	0	0.0	**255.7**
1	0.5	0.567	0.433	**110.7**
2	1.0	0.265	0.735	**81.4**
3	1.5	0.313	0.687	**55.9**
4	2.0	0.337	0.663	**38.0**
5	2.5	0.358	0.642	**24.3**
6	3.0	0.384	0.616	**15.0**
7	3.5	0.392	0.608	**9.3**

Meters of Water (1 metric ton per cubic meter density)	Equivalent meters of Regolith to equal each meter of water	Blocking % - amount of dose BLOCKED by each layer	Reduction Factor (% of remaining dose)	Radiation (mSv/year) received below each layer
8	4.0	0.40	0.60 (est)	**5.76**
9	4.5	0.40	0.60 (est)	**3.6**
10	5.0	0.40	0.60 (est)	**2.2**

This calculated progression of 10 meters does not provide quite the same level of protection as the Earth's atmosphere, which reduces the cosmic radiation component of background radiation to about 0.3 mSv/year, so there may be a significant under-estimation of its effectiveness. It indicates that only about 3 meters of regolith at the given density would be needed for full protection (down to accepted civilian dose levels, with 4 meters needed for pregnant women and children), but actual tests and measurements would be needed to verify this.

Since the crew would be inside the buried habitats most of the time, they would not accumulate much of a dose. However, a significant amount of the work must be done outside. The average dose of about 0.7 millisieverts per day outside on the surface would not create an immediate health risk, but a Carrington event level solar storm would. According to one paper, the "full spectrum" of radiation types from a Carrington event could give a person a dose of 5 millisieverts per hour, so if a solar storm lasted for 1 day, they would get a dose of 125 millisieverts. This is close to the maximum emergency dose for a radiation worker. The authors recommend that astronauts working on the surface have space weather alerts as needed, along with dosimeters and some means of getting to a radiation shelter (Guo, et al., 2017).

F.4 Hard Shell vs Expandable Habitats

Other estimates have said that hard shell habitats or inflatable crew habitats might need to be buried under up to 5 meters of regolith for inexpensive radiation protection, with easy access via stairwell-airlock modules. The habitats are similar to space station habs, about 4.5 meters in diameter and 8 meters long. The airlocks would be at the top of the stairwells. Stairs are needed since the living level is below ground. The airlock modules with stairwells are separate modules from the habitats and would be attached to the habitats before the habitat modules are buried. Additional habitats would be added as needed for work areas and plant growth**.** Some parts of the life support system need to be outside the pressurized area for practical and safety reasons.

The airlock doors have dust covers to keep dust away from the hatch. Mars dust does not seem to be abrasive like lunar dust, since wind and in some placed ancient flows of water have rounded most of the grains of fine sand and dust, but low levels of perchlorates could be toxic to the crew. The airlock chamber would have a shower in it to wash off any Mars dust and perchlorates off the Mars suit before the person enters the inner door. The dust is collected in a filter system and the water is recycled. Two redundant airlock systems are needed for each base habitat complex.

Figure 9.14: Rounded (non-abrasive) 0.3 mm grains of Mars sand (magnified) from Bagnold dune field – Curiosity Rover (NASA/JPL-Caltech/MSSS, 2017)

There are good arguments for the use of expandable Bigelow type modules in orbit. However, if used directly on the surface, the issue of radiation shielding and flooring needs to be investigated. A lot more shielding would be needed for a wider module. Existing inflatable modules consist of a hard core, with airlocks rigidly attached at each end, and the expandable section around it. This design works well in microgravity. For surface use, however, the inside of an inflatable would need to be redesigned, to allow floor areas below, above and on both sides of the rigid core structure. The core would also need to be supported against Mars gravity, and the supports would need to rest on the inflatable floor of the habitat. Due to the size of expandable modules, it is harder to place them in trenches and cover them with regolith, which could damage the outside layers. One solution is to put them under rigid Quonset shells, and cover the shells with regolith. The ends would also need to be protected by large regolith-filled "sandbags". In spite of the fact that the exteriors of the expandable habitats are fairly rigid due to the pressure, they will not be truly stable even if sitting in a trench. This issue still needs some work to arrive at practical solutions and designs.

F.5 Crew phase

Once at least 100 tons of liquid hydrogen and oxygen are produced (taking about 1 month), a ferry can return to orbit for another load, or some of the crew members can arrive at the base in a crew ferry, assured that they now can return to orbit. How soon the crew arrives depends on how important the crew's on-site oversight of robot operations is. The crew could arrive before or after the first crew habitat is buried.

Habitat module burial would involve excavating trenches for and burying the first crew module, connector modules and stairwell tubes to provide very good radiation protection for the crew. Connections for 4 adjacent habitat modules or air locks would be left exposed in the trench so that additional modules can be added. At least two airlock modules with their attached stairwell tubes would also be attached to the ends of modules. The 4.5 meter diameter modules would then be buried so that their ceilings would be about level with the surface, and the removed regolith would be dumped on top of them. The excavator used to dig these trenches would need to dig even deeper to reach the near-surface ice deposits, so the exact depth of the habitat depends more on the design rather than the radiation level. The regolith overburden of course, weighs only about 0.95 ton per cubic meter, due to the 0.38% gravity, assuming the regolith is 2.0 tons of mass per cubic meter.

From density of materials list at one site (Walker R. , 2016), the density of broken basalt, a typical material found right on the surface of Mars, forming most of the regolith in most areas, is about 2 metric tons per cubic meter, while solid basalt is about 3.0 metric tons per cubic meter. There is no known granite on Mars but sedimentary rocks would be less dense than basalt. If we assume that the spaces between the broken pieces of basalt in the regolith have been filled in with fines, we can assume the density is about 2.5 metric tons per cubic meter. Al Globus's tests with the radiation dose software OLTARIS (Globus, Personal communication, 2016) indicate that 9 tons of basalt per square meter is needed compared to only 5 tons of water to reach the 20 mSv/yr level require for civilians. Assuming that the regolith is 2.5 times as dense as water, we need about 3.6 meters of the regolith, or just under 12 feet. Some indicate that the density of Mars surface materials could be as low as 1.5 tons per cubic meter.

Also note that it is not absolutely mandatory for a crew to be protected to the 20 mSv/yr level since they will not be staying there for a lifetime. However, since all it takes is digging and dumping regolith, at a location where there is plenty of it, why not. An excavator designed for use on Mars may need extra weights on it and better grousers (cleats) on its treads to get a better grip on the ground when pushing into the regolith to dig. A backhoe is also an efficient deep digging method. If your base site is on a solid basalt lava flow, you cannot dig at all, so site selection is important.

With radiation protection for the crew established in at least one habitat module, the next load of ferry cargo could be the solar power plant. It would assure the survival of the crew in the habitats even if All the reactors failed. Due to the low gravity and lack of strong wind, the solar arrays can be very lightly built. The solar array would be laid out very similar to those on Earth, with 25% of the side area covered with arrays and 75% a separation to prevent shadowing. Again, power cables in trenches would carry the power to a central battery pack and then to the habitat. Additional ferry loads would bring down other cargo such as long range pressurized rovers, local ATV type (riding) rovers, radio dishes, a radio tower for local line of sight communications, and probably equipment to grow food plants in one of the habitat modules.

Once all of the crew's essentials such as a huge food supply are safely stored at the base, a lot of science and laboratory equipment would be brought down and base science operations, including geology, minerology, exobiology and meteorology, could begin. This would include drilling equipment and would allow geologists to directly date the Mars rocks and soil, allowing a more +accurate geologic record of the base area to be established.

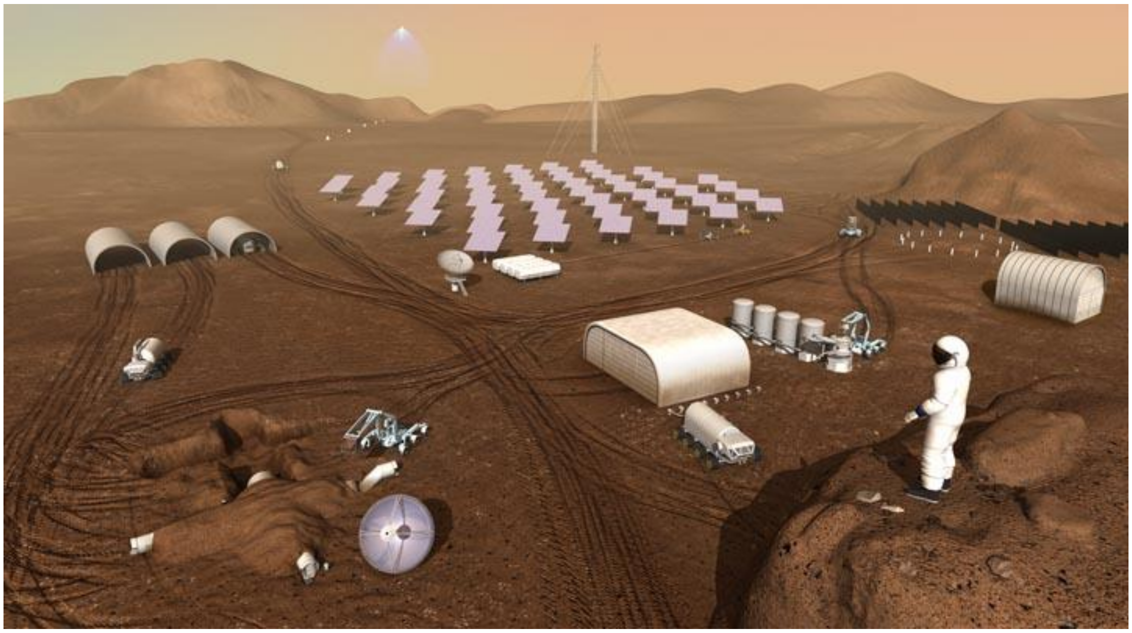

Figure 9.15: Mars Science Base [Anna Nesterova]

Figure 9.16: Mars Science Base - Buried Habitat Area [Anna Nesterova]

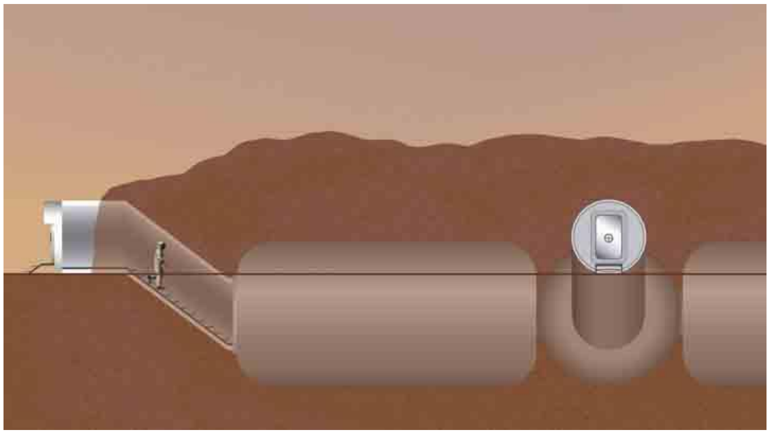

Figure 9.17: Mars Science Base Habitat Cross section [Anna Nesterova]