AIAA 2015-4565

SPACE Conferences & Exposition
31 Aug-2 Sep 2015, Pasadena, California
AIAA SPACE 2015 Conference and Exposition

50-year Window to Establish a Space Faring Civilization

A. Scott Howe, PhD[1]
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109

Humankind may only have a short window of 50 years to become a space-faring civilization, after which time the opportunity to do so may become too difficult or impractical to pursue. Current policies for space exploration and infrastructure development implicitly assume a gradualistic approach to technology, budgets, and mission execution -- the common thought has been that there will be plenty of time in humankind's future to become a space-based species, and whatever we are unable to accomplish will be borne by the generations that follow. However, considering natural events, available energy, and human tendencies, the timing to make the most effective effort to achieve multi-planet status might be now, before momentum is lost and we become distracted by Peak Oil and changing energy economies -- restarting a space program after such turmoil may be more difficult than would be practical without cheap, storable, high-energy density petroleum. "Space-faring civilization" is defined as an economically profitable space-based economy that demands the presence of humans off-world in order to sustain a high level of prosperity. An initial foothold for a space-based economy that would fit within the 50-year window might include Earth dependence on rare-earth elements or other hard-to-obtain minerals mined from moons or asteroids, or a permanent settlement on another planet. Using published sources, notional mass and energy requirements for a minimal self-sustaining Mars settlement is calculated, and the number of launch vehicles discussed. Setting the launch schedule to match that of current NASA projections, it could take more than 26 years of semi-annual launches to build up such a self-sustaining human settlement -- a cost and

commitment that has not been acknowledged nor planned for. Considering the time required to establish a multi-planet species, this paper frames the required window of decision that, if not taken, could condemn the species to Earth subject to whatever natural or human-made calamities that endanger single-planet civilizations.

Nomenclature

ATHLETE	=	All-Terrain Hex-Limbed Extra-Terrestrial Explorer wheeled mobility system
ECLSS	=	Environmental Control and Life Support System
ELE	=	Extinction Level Event
EVA	=	Extra-Vehicular Activity
FACS	=	Freeform Additive Construction System
GCR	=	Galactic Cosmic Radiation
ISRU	=	In-Situ Resource Utilization
ISS	=	International Space Station
NASA	=	National Aeronautics and Space Administration
NEA	=	Near Earth Asteroid
NEAR	=	Near Earth Asteroid Rendezvous project
SLS	=	NASA's Space Launch System
SPE	=	Solar Particle Event

I. Introduction

SMART people have long known that humans will eventually want to explore beyond the Earth. In 1610 Johannes Kepler speculated to Galileo, "As soon as somebody demonstrates the art of flying, settlers from our species of man will not be lacking [on the moon and Jupiter] . . . Given ships or sails adapted to the breezes of

[1] Space Architect, Senior Systems Engineer, a.scott.howe@jpl.nasa.gov

heaven, there will be those who will not shrink from even that vast expanse" (Rosen 1965). More recently, once the nature of the "breezes of heaven" had become understood, Hermann Oberth declared, "This is the goal: To make available for life every place where life is possible. To make inhabitable all worlds as yet uninhabitable, and all life purposeful" (Oberth 1957). When doubters wondered if humans belonged in space, Werner von Braun defended, "Don't tell me that man doesn't belong out there. Man belongs wherever he wants to go--and he'll do plenty well when he gets there" (Time Magazine 1958). One of the pioneers of human spaceflight, and the first person to set foot on the moon, Neil Armstrong humbly pointed out the implications of his achievement: "In my own view, the important achievement of Apollo was a demonstration that humanity is not forever chained to this planet, and our visions go rather further than that, and our opportunities are unlimited" (Armstrong 1999). The thought that a pre-space civilization could become no more than a historical footnote was wittily captured by Arthur C. Clarke in an interview: "If man survives for as long as the least successful of the dinosaurs—those creatures whom we often deride as nature's failures—then we may be certain of this: for all but a vanishingly brief instant near the dawn of history, the word 'ship' will mean—'spaceship.' " (Downs 2008). And taking the spaceship idea further, Buckminster Fuller acknowledged that we are already on a spaceship traveling through a remote corner of space; "For at least 2,000,000 years men have been reproducing and multiplying on a little automated spaceship called earth" (Fuller 1964). Fuller further likened our fossil fuel supply to an automobile battery on "Spaceship Earth", needed as an initial jump start (Fuller 1969) or venture capital to obtain additional fuel and resources from the space environment.

There seems to be a prevalence of thinking that Earth is all there is, and that resources are limited: "Unless people can see broad vistas of unused resources in front of them, the belief in limited resources tends to follow as a matter of course. And if the idea is accepted that the world's resources are fixed, then each person is ultimately the enemy of every other person, and each race or nation is the enemy of every other race or nation. The extreme result is tyranny, war and even genocide. Only in a universe of unlimited resources can all men be brothers" (Zubrin

1996). Far-thinking individuals have realized that becoming a space-faring civilization is not an option but a necessity. O'Neill (1978), echoed more recently by Lewis (1996), explained, "Clearly our first task is to use the material wealth of space to solve the urgent problems we now face on Earth: . . . to provide for a maturing civilization the basic energy vital to its survival." With endless environmental concerns, Patrick Collins and Adriano Autino have proclaimed that "the Earth is not sick, she is pregnant", about to give birth to a space-faring society. Expansion into near-Earth space is the only alternative to endless "resource wars" (Collins & Autino 2008). Others have used the birth metaphor as well. Science fiction author Robert Heinlein spoke through one of his characters, Jacob Salomon, "It may take endless wars and unbearable population pressure to force-feed a technology to the point where it can cope with space. In the universe, space travel may be the normal birth pangs of an otherwise dying race. A test. Some races pass, some fail" (Heinlein 1970). Noted rocket propulsion engineer Krafft Ehricke (1981) also likened our world to a space civilization about to be born: "To think that we could stop growing could be compared to an imaginary embryo that is in its sixth or seventh month and has decided to stop growing in order to survive in the womb . . . It decides this growth is impossible, so that it had better stop growing . . . before a catastrophe occurs. What it doesn't know is that in the ninth month a change will take place . . . 'Mother' Earth and her latest children, humanity, are at that same point now. Our new frame of reference will be the environmental enlargement beyond Earth. Now that we possess the necessary technology, we can 'breathe' and live beyond Earth, outside the womb of the biosphere in which we grew up."

There is a well-known Larry Niven quote, as related by Arthur C. Clarke, "The dinosaurs became extinct because they didn't have a space program. And if we become extinct because we don't have a space program, it'll serve us right!" (Chaikin 2001). Experts see the situation as being more urgent than geological time scales. Former NASA administrator Michael Griffin said point blank, "In the long run, a single-planet species will not survive" (Washington Post 2005). The very survival of the human race depending on our settling off-world has been advocated by Sagan (1994): "Since, in the long run, every planetary civilization will be endangered by impacts from [illegible] or romantic zeal, [illegible] e, we have a basic [illegible] nly move forward: [illegible] Though men and civilizations may yearn for rest, for the dream of the lotus-eaters, that is a desire that merges imperceptibly into death. The challenge of the great spaces between the worlds is a stupendous one; but if we fail to meet it, the story of our race will be drawing to its close" (Clarke 1960; Clarke & Macauley 2001). Savage (1994) described a failure to act as unthinkable: "In the next few galactic seconds, the fate of the universe will be decided . . . If we deny our awesome challenge; turn our backs on the living universe, and forsake our cosmic destiny, we will commit a crime of unutterable magnitude . . . This is perhaps the first and only chance the universe will ever have to awaken from its

long night and live. We are the caretakers of this delicate spark of Life. To let it flicker and die through ignorance, neglect, or lack of imagination is a horror too great to contemplate."

There may be less time to become a space-faring civilization than most think. The warnings are numerous. Elon Musk, founder of SpaceX said, "To our knowledge, life exists on only one planet, Earth. If something bad happens, it's gone. I think we should establish life on another planet—Mars in particular—but we 're not making very good progress" (Thomas 2007). He also pointed out, "It's important that we attempt to extend life beyond Earth now. It is the first time in the four billion-year history of Earth that it's been possible and that window could be open for a long time—hopefully it is—or it could be open for a short time. We should err on the side of caution and do something now" (Harris 2010). Writer Ben Bova argues that humanity's survival depends on the colonization of space, "A new space race has begun, and most Americans are not even aware of it. This race is not [about] political prestige or military power. This new race involves the whole human species in a contest against time" (Bova 1981). "We hesitate about where to go from here in space. Yet our delay in exploiting this window of opportunity could close off choices for our descendants . . . It may be up to us to prove that intelligence armed with technology has long-term survival value" (Michaud 1979). Futurist Barbara Marx Hubbard once said, "I believe it is urgent to begin now, before we are constrained by a totally controlled society monitoring limited resources on the planet. Now is the time to establish our extraterrestrial base in freedom; later it may be under the coercion of necessity" (Hubbard 1977).

England's Astronomer Royal, Sir Martin Rees warns, "Will the self-sustaining space communities be established before a catastrophe sets back the prospect of any such enterprise, perhaps foreclosing it forever? We live at what could be a defining moment for the cosmos, not just for our Earth" (Rees 2003). "This generation is crucial; we have the resources to get mankind off this planet. If we don't do it, we may soon be facing a world of 15 billion people and more, a world in which it's all we can do to stay alive; a world without the resources to go into space" (Pournelle 1979). Astronaut Philip Chapman wrote, "Our generation may stand at a crucial breakpoint in history, for we in the presently affluent nations may be the last who can afford to open up the high frontier. What we do during the next ten or twenty years may determine whether future generations will live in a humane and rewarding society, or whether they will spend their lives in desperate contention for the dwindling sustenance afforded by our limited terrestrial resources" (Chapman 1978).

Finally, cosmologist Richard Gott III wrote, "There may be only a brief window of opportunity for space travel during which we will in principle have the capability to establish colonies (which could in turn establish further colonies). If we let that opportunity pass without taking advantage of it we will be doomed to remain on the Earth where we will eventually go extinct" (Gott 1993).

But how much time do Homo sapiens have? Is there a basis for all these concerns and warnings that can be quantified? This paper uses peer-reviewed literature to discuss timelines for a series of well-known potential obstacles to human spaceflight development that could prevent the establishment of a space-faring civilization. Starting with the four billion year deadline when the sun becomes a red giant and expands past the orbit of the Earth, a countdown that includes statistical impacts of Near Earth Objects (NEOs), and peer-reviewed discussions of possible human-caused calamities narrow the window -- obvious events that, though potentially far off, would require the establishment of a human presence beyond Earth in order for the species to survive. Finally, the paper concludes with an argument for a 50-year window based on distractions from peak oil (Peak Oil 2014) and changing energy economies.

II. Notional Mass Requirements for a Minimal Mars Settlement

How much would it cost to put the human race on more than one planet? Popular physicist Paul Davies pointed out that, "A Martian colony could keep the flame of civilization and culture alive until Earth could be reverse-colonized from Mars" (Davies 2004). Detailed model-based estimates for establishing off-Earth mining scenarios supporting the human colonization of Mars have been proposed or are in progress (Shishko, et al 2015). For the purposes of this paper, previously published sources will provide a rough, though undoubtedly optimistic basis for establishing a starting estimate from which to work from.

When sending something into space, the mass of the proposed payload becomes the critical driver. The target mass tells how much fuel will be needed to lift it out of Earth's gravity well, which is the most technically difficult to manage. Working back from the mass, one would either find a launch vehicle capable of launching that mass, or figure out how to divide the payload into manageable manifests that do not exceed the capacity of multiple rocket launches.

It is possible to imagine or even predict a distant future scenario, where there is complete knowledge of the world's range of genomes and alleles, and there is a functional understanding of the implications of genetic engineering of designer organisms (Koebler 2015). With thousands of exoplanets being discovered, it is likely that a

habitable planet will be found that could be a good candidate for colonization. Assuming that a launch vehicle could be developed that could carry a payload to these distant star systems, no matter how many thousands of years the journey, it would definitely be more practical to engineer some organisms to prepare the planet for eventual human habitation (Fogg 1995; Beech 2009) than it would be to send a gigantic, budget-busting generation ship. An efficient scenario would be to start with a small, low-mass package, load dormant genes into a simple single-celled organism ("junk" DNA) designed to switch on or off depending on environmental cues, or engages in horizontal gene transfer to modify germ cells, that slowly executes pre-loaded evolution to build up complexity in the biosphere. Initial organisms would thrive in the harsh environment, and genes would switch on or off as the atmosphere thickens to cause the organism to evolve into more complex and even multi-celled organisms. Engineers will be able to electronically "fax" changes to the genome as needed (Venter 2013, ch 4; Venter 2013 ch 11). Could future engineers pack such potential into an engineered genome to eventually give birth to thinking, breathing human beings? Unfortunately the human race likely does not have the time to develop such technologies before it is forced to establish a human settlement off Earth. It will be necessary to start with the technology on hand and begin immediately on a planet within reach that is already known. Until such an advanced genetically engineered compact colonization technology is perfected, live human crews that require a lot of mass will have to be sent.

For human missions, mass can be calculated from the number of crew and duration of the mission. Since the cost of setting up a permanent settlement is under consideration, the mission duration would have no end -- instead it would be necessary to figure out how to keep the crew alive using self-sustaining regenerative systems. In addition, the colony would need to ease into manufacturing capabilities to allow them to gradually wean themselves from Earth resupply and become independent. In calculating the minimal cost of setting up a settlement, it will be necessary to figure out the number of crew required, mass of structures, mass of regenerative life support systems, and mass of manufacturing capability to keep the settlement alive.

The number of crew members required to form a self-sustaining settlement away from Earth would depend on maintaining the most precious asset: the gene pool of the human race. Note that the following calculations are strictly a minimum for preserving the human gene pool and all its diversity by keeping a minimal population alive for several generations on a Spartan vegetarian diet. The cost of transporting animal stock or transplanting entire self-contained plant/animal ecologies and their gene pools is neglected -- it would be naïve to assume the human race could survive perpetually without such.

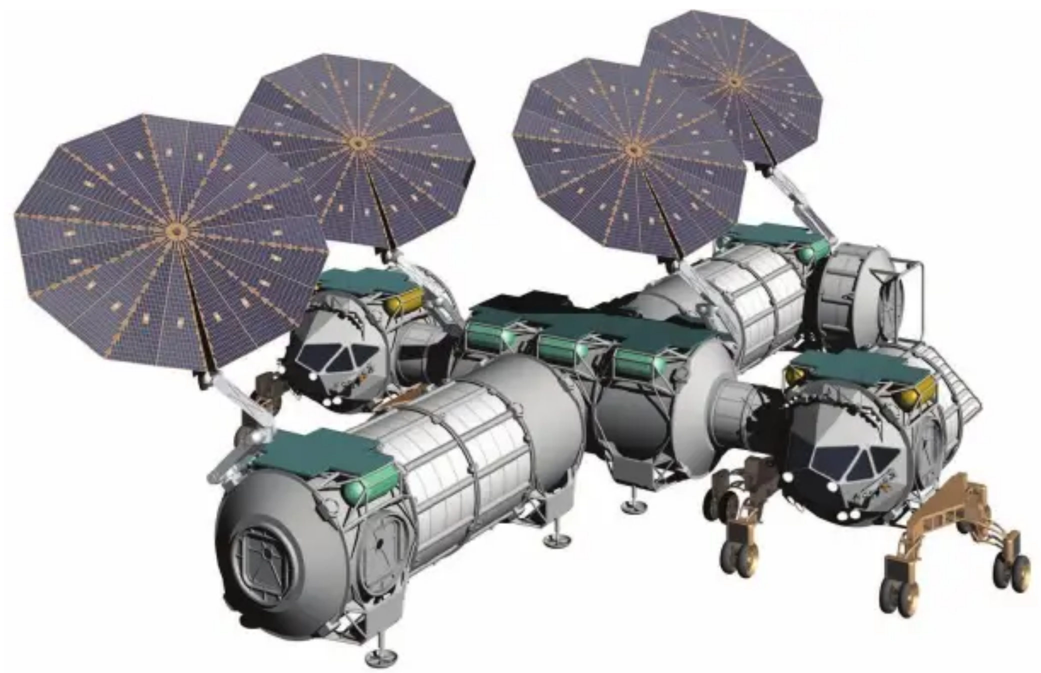

Figure 1: Initial pressurized modules clustered together showing core modules, Midex modules, vehicles, and airlocks. Modules can be arranged for Mars settlement planning and zoning (Howe 2015)

There are differing opinions on how many individuals are required to maintain a healthy gene pool. On the high end anthropologist Cameron Smith (Smith 2013) argues that a robust multi-generational colony population needs to be at least 20,000-40,000 individuals in order to cover racial diversity, allele range, and redundancy. A population of 50 has an inbreeding rate of 1% per generation, about half the maximum tolerated by domestic animal breeders.

Therefore a more manageable rule of thumb may be the 50/500 rule by Franklin and Soule (Franklin 1980), where 50 individuals are assumed to be the bare minimum to prevent unacceptable inbreeding, but a population of 500 would maintain genetic variability.

Table 1: Habitation parameters for a crew of 4 + 46 for a permanent Mars settlement

		Totals	**2,000**	**kW**	**995,003**	**kg**	**4,222**	**m3**	**1,113**	**m2**
Crew Size			Power		Mass		Volume		Floor Area	
4	persons	*Habitat*	40	kW	11,328	kg	3,140	m3	1,113	m2
Dormant Crew		*Laboratory*	90	kW	7,790	kg				
46	persons	*Structures*			166,054	kg				
Mission Duration										
730	days	*Greenhouse*	298	kW	619,220	kg	875	m3		
			(Doll 1999)		(Drysdale 2008)		(Tako 2010)			
		Rover Vehicles	30	kW	72,611	kg	207	m3		
		Factory	2,000 (Freitas 1980)	kW	118,000	kg				

However, since this effort is trying to accomplish the task of setting up a permanent settlement with the least amount of mass, a smaller crew including at least one or two women who are capable of having multiple children in vitro might be all that is needed (Space Colonization 2014). Hundreds of fertilized embryos included in the payload could begin to fill out a population, and children born in vitro from the same mother would be free to pair up without worry of genetic errors creeping in. In addition to natural children, women from multiple generations would be able to give birth to the in vitro crewmembers until the threshold population is reached and beyond.

Therefore, for a minimal mass settlement, the assumption will be an initial crew of four on Mars (it would be possible to assume a minimalistic "Adam and Eve" couple, but the number four was chosen for redundancy). Unfortunately, sending only a small crew of four may not be as advantageous as it sounds, since it would still be necessary to send enough biomass for the yet unborn crew members, and enough pressurized volume to grow plants for the bio-regenerative life-support system and food production.

As an initial seed mission, it is assumed that two years of core physio-chemical life support (Oxygen Generation Assembly air revitalization, Multi-Filtration water revitalization; Doll & Eckart 1999, p554) will be needed until the bio-regenerative life support systems (using plants for food production and air/water revitalization; Nelson, et al 2009; Wheeler 2010; Tako, et al 2010; Doll & Eckart 1999, p561) can take over.

Using a modular habitation system (Howe 2015) with "Core Hab" units fitted with equipment and semi-inflatable “Midex” units that deploy to create usable pressurized volume, habitation (Table 2, Stilwell, Boutros & Connolly 1999; p596), laboratory (Table 3), and greenhouse functions can be accommodated for four initial crew members plus an additional 46 who will occupy the outpost later. Initial outfitting will require 10 Core Hab modules (Figure 2, left) and 56 Midex modules (Figure 2, right) for a total of 166,054kg mass and 4,015m^3 volume when fully deployed and operational (Table 4). In addition, the calculations include one pressurized rover vehicle (Figure 3) for every five crew (Table 4, Table 5), for a total of ten vehicles.

The 66 modules and ten rover vehicles provide a seed outpost (Figure 1) that will be adapted and expanded upon as the settlement grows and generations of crewmembers increase the population. In this study, power requirements were fulfilled by an In-Situ Resource Utilization (ISRU) factory that will have significant power requirements -- the habitable areas will not provide a significant load on the power system compared to the various excavation, fabrication, and assembly functions in the factory (at least not in this study). 2,000kW of power will require 58,000kg (Hanford 2004, p18) of modular nuclear fission power units (Table 6), which would be less mass than the solar or fuel cell options. However, a self-sustaining settlement would immediately put solar and fuel cells into production to eventually replace or augment the nuclear system.