AIAA 2015-4565
SPACE Conferences and 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 space, every surviving civilization is obliged to become spacefaring--not because of exploratory or romantic zeal, but for the most practical reason imaginable: staying alive... If our long-term survival is at stake, we have a basic responsibility to our species to venture to other worlds." Arthur C. Clarke believed we must only move forward: "There is no way back into the past; the choice, as Wells once said, is the universe—or nothing. 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.

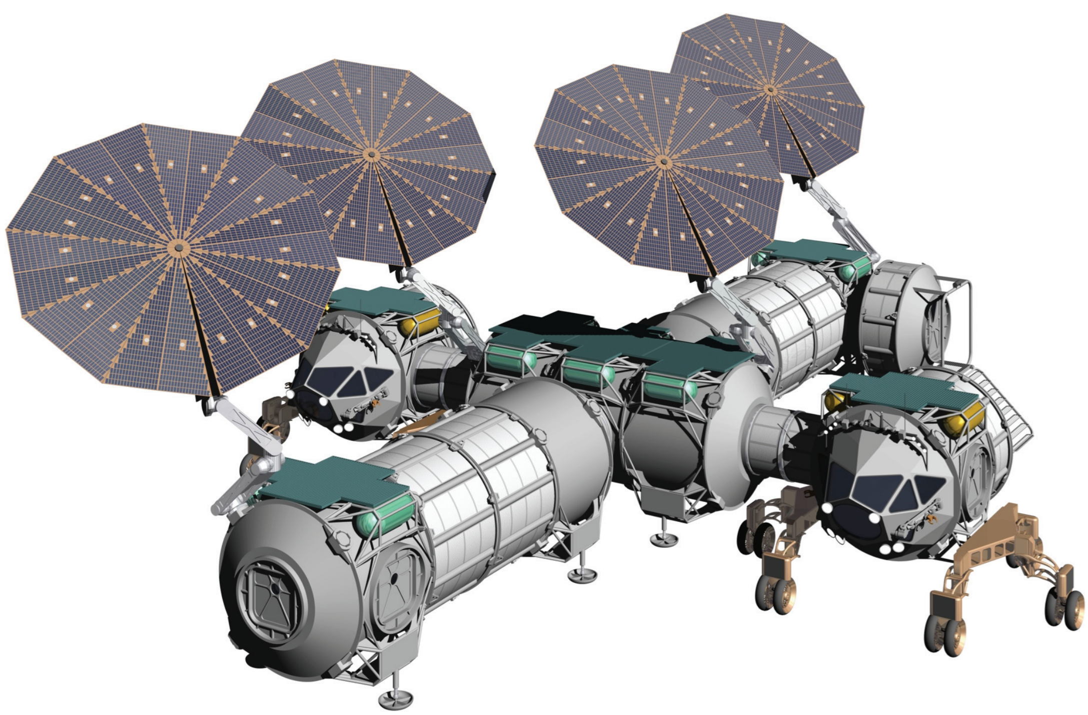

Figure 1: Initial pressurized modules clustered together showing core modules, Midex modules, vehicles, and airlocks. Modules can be arranged for Mars settlement planning and zoning (Howe 2015)

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

Crew Size	
4	persons
Dormant Crew	
46	persons
Mission Duration	
730	days

Totals	**2,000**	**kW**	**995,003**	**kg**	**4,222**	**m3**	**1,113**	**m2**
	Power		Mass		Volume		Floor Area	
Habitat	40	kW	11,328	kg	3,140	m3	1,113	m2
Laboratory	90	kW	7,790	kg				
Structures			166,054	kg				
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	kW	118,000	kg				
	(Freitas 1980)							

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.

Table 2: Initial habitat function details for four crew for a 730 day seed period for permanent settlement (based on Stilwell, Boutros & Connolly 1999)

Habitat Functions	**11,328**	**kg**	**112.15**	**m3**	**40**	**kW**
Galley and Food System	Mass		Volume			
Food	6,716	kg	23.36	m3		
Freezers (mass & volume does not include food)	400	kg	2.00	m3		
Conventional Ovens	50	kg	0.25	m3		
Microwave Ovens	70	kg	0.30	m3		
Kitchen / Oven Cleaning Supplies	1	kg	1.31	m3		
Sink, Spigot for Hydration Food & Drinking Water	15	kg	0.01	m3		
Dishwasher	40	kg	0.56	m3		
Cooking / Eating Supplies	20	kg	0.06	m3		
Waste Collection System	Mass		Volume			
System	90	kg	4.36	m3		
WCS Supplies	146	kg	3.80	m3		
Contingency Fecal and Urine Collection Bags	672	kg	2.34	m3		
Personal Hygiene	Mass		Volume			
Shower	75	kg	1.41	m3		
Handwash / Mouthwash Faucet	8	kg	0.01	m3		
Personal Hygiene Kit	7	kg	0.02	m3		
Hygiene Supplies (Consumables)	219	kg	4.38	m3		
Clothing	Mass		Volume			
Clothing (2.4kg per person per day up to 4 weeks)	269	kg	1.34	m3		
Washing Machine	100	kg	0.75	m3		
Clothes Dryer	60	kg	0.75	m3		
Recreational Equipment & Personal Stowage	Mass		Volume			
Personal Stowage	200	kg	0.75	m3		
Housekeeping	Mass		Volume			
Vacuum (Prime + 2 Spares)	13	kg	0.07	m3		
Disposable Wipes for Housekeeping	0	kg	0.00	m3		
Trash Compactor / Trash Lock	150	kg	0.30	m3		
Trash Bags	146	kg	2.92	m3		
Sleep Accommodations	Mass		Volume			
Sleep Provisions (Sleep Restraints Only)	36	kg	0.40	m3		
Crew Health Care	Mass		Volume			
Exercise Equipment	145	kg	0.19	m3		
Medical / Surgical / Dental Suite	1,000	kg	4.00	m3		
Medical / Surgical / Dental Consumables	500	kg	2.50	m3		
Operational Supplies & Restraints	Mass		Volume			
Operational Supplies (data storage, ziplocks, etc)	80	kg	0.01	m3		
Restraints	100	kg	54.00	m3		

Table 3: Initial laboratory function details for four crew for a 730 day seed period for permanent settlement (based on Stilwell, Boutros & Connolly 1999)

Laboratory Functions	**7,790**	**kg**	**37.80**	**m3**	**89.50**	**kW**
Maintenance / Fabrication: All in Habitable Areas	Mass		Volume			
Hand Tools and Accessories	300	kg	1.00	m3		
Spare Parts & Consumables	70	kg	0.50	m3		
Test Equipment (Oscilloscopes, Gauges, etc)	500	kg	1.50	m3		
Fixtures, Large Machine Tools, Gloveboxes, etc	1,000	kg	5.00	m3		
Additive Manufacturing Machine	40	kg	0.20	m3		
Sheet Metal Machine (Finger, Brake, Shear, Roller)	50	kg	0.20	m3		
Desktop 3D Milling Machine (CNC)	75	kg	0.20	m3		
Air Compressor	100	kg	0.50	m3		
Vacuum Cleaner	10	kg	0.10	m3		
Photography	Mass		Volume			
Equipment (Still & Video Cameras, Lenses, etc)	120	kg	0.50	m3		
Human Physio-Chemical ECLSS						
Air Revitalization System (OGA)	1,750	kg	1.50	m3	17.50	kW
Air System Spares & Misc	1,100	kg	4.50	m3		
Water Revitalization System (MF)	500	kg	2.00	m3	2.00	kW
Water System Spares & Misc	1,500	kg	4.50	m3		
Animal Physio-Chemical ECLSS						
Air Revitalization System (OGA)	0	kg	0.00	m3	0.00	kW
Air System Spares & Misc	0	kg	0.00	m3		
Water Revitalization System (MF)	0	kg	0.00	m3	0.00	kW
Water System Spares & Misc	0	kg	0.00	m3		
EVA Suit	Mass		Volume			
Suit	120	kg	4.00	m3		
Suit Mission	360	kg	11.60	m3		
Consumables	32	kg				
EVA Tools and Equipment	Mass					
Maneuvering Unit	0	kg				
EVA Tools	123	kg				
EVA Work Aids	40	kg				

Table 4: Structure volumes and masses for pressure modules and vehicles (based on Howe 2015)

Mass	**166,054**	**kg total**			**Mass**	**72,611**	**kg total**
Core Hab	10	modules	2,571.3	kg each	Vehicles	10	cabins
Habitat	0	modules	2,533.4	kg each	(Table 5)	Habitable Volume	
Midex	56	modules	2,421.7	kg each		141	m3
Airlock	5	modules	944.9	kg each		Total Volume	
						207	m3
Floor Area	1,113	m2				Additional Units	
Volume	4,015	m3				0	Units
Stowed	2,645	m3					

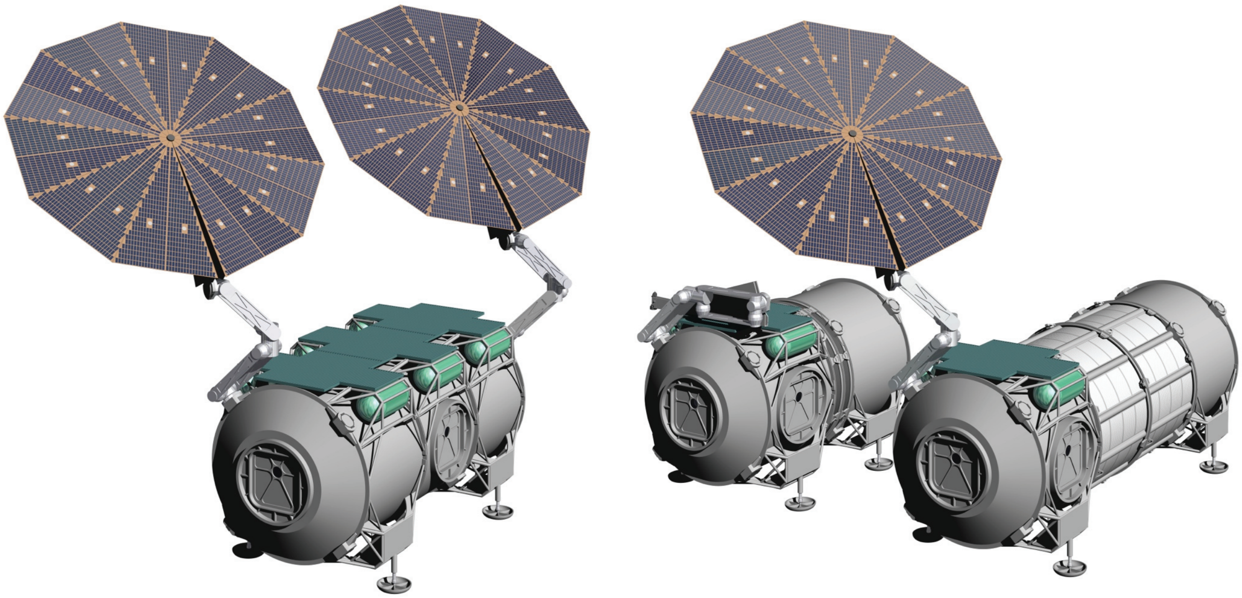

Figure 2: Core Habitation module (left), and Midex module (right, showing stowed and expanded configurations; Howe 2015)

Table 5: Mass and volume calculations for pressurized rovers (surface vehicles for crew: adapted from Abercromby, et al 2012; Gernhardt & Abercromby 2008; Wilcox 2012)

Mass per Vehicle (kg)	7261	Pressurized Vol (m3)	20.7	Habitable Vol (m3)	14.1

Design Constraints / Parameters		
Pressurized Vol.	20.7	m3
Habitable Vol.	14.1	m3
Max Crew Capacity	4	persons
Crewed Mission Duration	14	days
Est. power, uncrewed	1.5	kW
Est. power, crewed	2	kW
Solar power generation	3	kW
Total Batter Energy Storage	100	kW-h
Depth of Discharge	80	%
ECLSS System	open loop	
Max Speed		km/hr
Range	10	's of km
Max. Length	5.5	m
Max. Width	7.9	m
Max Height	4.35	m

Category	Mass (kg)	
	Cabin	Mobility
Structure	1,577	1,598
Protection	40	
Thermal	643	
Power	370	
Control	55	
Avionics	145	
Other	120	
Growth	885	480
DRY MASS SUBTOTAL	3,835	2,078
Non-cargo	10	0
Cargo	957	0
INERT MASS SUBTOTAL	4,802	2,078
Non-propellant	381	0
Propellant	0	0
TOTAL WET MASS	5,183	2,078

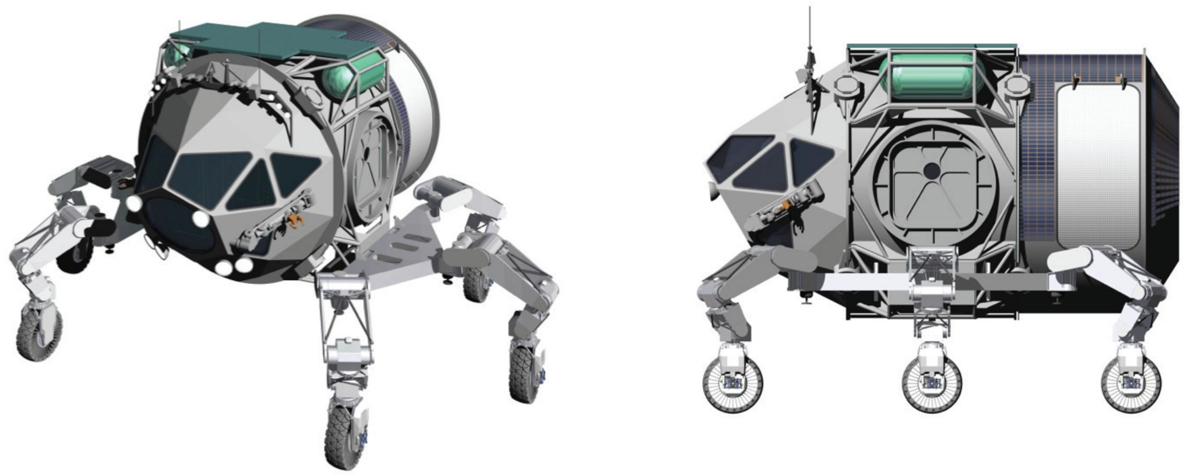

Figure 3: Pressurized rover vehicles for surface travel (Abercromby, et al 2012; Gernhardt & Abercromby 2008; Howe 2015)

For this study a flexible rover mobility system was chosen called the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system, shown in Figure 3 (Wilcox, et al 2007; Wilcox 2012). The ATHLETE limbed wheel vehicles can be detached from the rover pressurized cabin and utilized for other work, such as construction, propellant production, and large-scale 3D printing of structures (Figure 4) using a FACS Freeform Additive Construction System (Howe, et al 2013; Howe, et al 2014), etc. The FACS system and other robotic elements will be able to construct additional pressurized volume for expansion of the settlement.

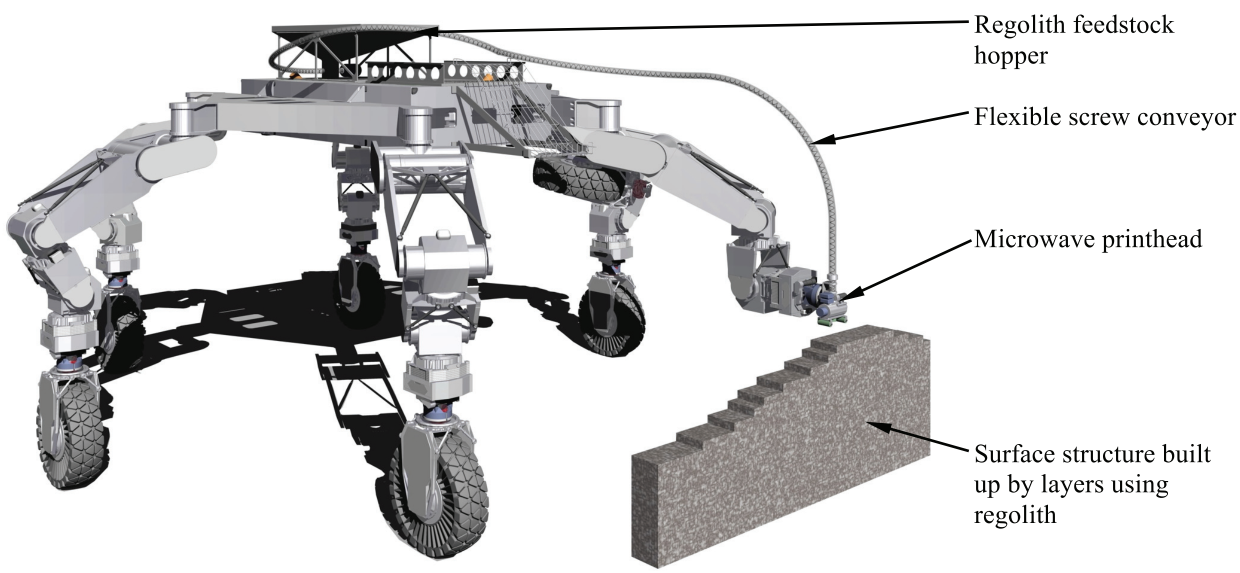

Figure 4: Freeform Additive Construction System (FACS) large-scale 3D printer for building additional structures using local materials (Wilcox, et al 2007; Wilcox 2012; Howe, et al 2013; Howe, et al 2014)

In 1980 NASA conducted a workshop that established mass requirements and energy needs for a semi-self-replicating lunar factory (Freitas & Gilbreath 1980), using available technology at the time (Table 6). In actuality, a self-replicating system using raw soil as an input has only been found in nature, though most experts believe engineers are close to being able to construct one artificially (Freitas & Merkle 2004). Assuming it will be possible to build a self-replicating factory for support of the permanent settlement, the 1980 mass estimates are significant, and would require 22 Falcon Heavy launches (a cheap, commercial rocket manufactured by SpaceX) just to get the factory to Mars. Though it is certain that a much lighter self-replicating factory system could be built using additive manufacturing and other numerical control modernized techniques, this study will start with the 1980 numbers since few studies of this type have been conducted and data is lacking.

Table 6: Mass and power requirements for a semi-self-replicating ISRU factory (adapted from Freitas & Gilbreath 1980; Hanford 2004)

Totals	2,000	kW	358,000	kg	118,000	kg	736,000	kg
	Power		Solar		Nuclear		Fuel Cell	
Transponder Network			1,000	kg	1,000	kg	1,000	kg
Paving Robots	10	kW	12,000	kg	12,000	kg	12,000	kg
Mining Robots	10	kW	4,400	kg	4,400	kg	4,400	kg
Chemical Processing Sector	1,705	kW	23,515	kg	23,515	kg	23,515	kg
Fabrication Sector	173	kW	10,269	kg	10,269	kg	10,269	kg
Assembly Sector Robots	10	kW	617	kg	617	kg	617	kg
Assembly Sector Warehouse Subsystem	10	kW	1,000	kg	1,000	kg	1,000	kg
Automated Transport Vehicles	6	kW	1,000	kg	1,000	kg	1,000	kg
Module Assembly and Repair Robots	40	kW	4,000	kg	4,000	kg	4,000	kg
Computer Central Orbital Site Map	37	kW	2,200	kg	2,200	kg	2,200	kg
Solar Canopy Power System			298,000	kg				
Nuclear Power System					58,000	kg		
Regenerative Fuel Cells + Solar							676,000	kg

From these assumptions, the calculations show that an initial optimistic estimate for a minimal permanent self-sustaining settlement on Mars would be 995,000kg of mass (Table 1) and would take 75 launches of the new NASA Space Launch System (SLS), or 184 Falcon Heavy launches at a transportation cost of 66.6 billion dollars. Considering development costs as well, the figure soars to 162 billion dollars (Guerra & Shishko 1999, p946; Space Launch System 2014; SpaceX 2013).

In 2013, NASA's budget was $17,934 million (NASA Agency Financial Report 2013), 0.47% (less than 1%) of the US national budget (Federal Budget 2013). Of that $4,229 million goes to science (planetary probes, rovers, monitoring carbon dioxide levels, global temperatures, measuring polar ice thickness, etc). $5,075 million of the budget goes to mission operations support, such as the maintenance of the International Space Station (ISS), the orbital laboratory that helps understand how to live and work in space for long periods of time. $1,242 million was spent on education, aeronautics, and technology development. That leaves $7,388 million a year for the establishment of a colony on Mars (funds currently being allocated to human exploration, such as the development of the Space Launch System).

Therefore at the going rate using the NASA SLS launch system, it would take 26 years to put a minimal colony on Mars. That time span could be decreased to 22 years using the cheaper commercial SpaceX Falcon Heavy vehicle and more launches. Or the space development budget could be increased, taking away from other important programs. Or the population could be increased to expand the tax base. Regardless, 22 out of 50 years does not leave a lot of room for establishing a space-faring civilization, especially since such an endeavor hasn't even been started yet.

III. Window for Establishing a Space Faring Civilization

How much time does the human race have to become a multi-planet species? It may be that the average person knows that eventually the human race will colonize space. There may be plenty of time to do so, and some of the hard decisions could be left to future generations that have better technologies, budgets, and less world problems and issues to deal with. Or, is it an urgent matter? This section will analyze a countdown of known, or predicted extinction deadlines that could become obstacles to the establishment of a sustainable off-world presence.

A. Four Billion Year Window

Aerospace engineer Thomas Heppenheimer wrote, "If humanity persists and endures, in time we will come face to face with the evolution of our sun. In a few billion years its slow brightening will speed up as it swells into a red giant. Earth will then be uninhabitable, as will the inner regions of the Solar System. Yet there will be other more clement stars to which our descendants may wish to migrate. Certainly a society that has developed space flight and space colonization will have the advantage of never thereafter having to stand hostage to fortune" (Heppenheimer 1979). Robert Shapiro (1999) contributed, "Earth has provided a stable platform for the evolution of life over 4 billion years. But that lease is limited; we know for sure that it will expire after a few billion more. Long before that, our planet may become a place where it is no longer suitable for us to live. Increasing luminosity of the sun may gradually boil our oceans, or more sudden catastrophes may threaten our existence. If we are wise, we will have furnished our new apartments long before that time."

There's already at least one natural extinction clock counting down already -- a deadline that can't be ignored. From what scientists have been able to estimate, the sun has been stable for over four billion years (Bonanno, Schlattl & Paternò 2008), and will be stable for another four billion. But after that it is thought that the sun will turn into a Red Giant and expand beyond the orbit of earth, completely engulfing the planet (Schröder & Smith 2008). Considering the life cycle of the sun, the human race will likely need to become a self-sustainable space-faring civilization before this four billion year deadline, whether that means moving away from Earth, or gaining the capability to move Earth to a more suitable orbit.

B. Hundred Thousand Year Window

"We must turn our guns away from each other and outwards, to defend the Earth, creating a global and in space network of sensors and telescopes to find asteroids that could destroy our planet and create the systems to stop them. It makes no sense to dream great dreams while waiting to be hit by a train" (Aldrin & Tumlinson 2006).

Policy makers and space agencies can be forgiven if they neglect to prepare for the planet's destruction four billion years later, but unfortunately there are likely other more immediate extinction countdowns. Werner von Braun once said, "I only hope that we shall not wait to adopt the program until after our astronomers have reported a new and unsuspected aster[oid] moving across their fields of vision with menacing speed. At that point it will be too late!" (von Braun 1953). It has been hypothesized that, 65 million years ago, an asteroid several kilometers wide hit the earth around Chicxulub, Mexico, and caused an Extinction-Level Event (ELE). An ELE is one in which environmental conditions become sharply inhospitable to some species, and they die off. The event in question is said to have been the one that wiped out the dinosaurs (Schulte, et al 2010). Though the scenario proposed by the Chicxulub asteroid event is controversial, the fact that asteroids and meteors regularly pass nearby and even impact the earth with surprising regularity is well known. An estimated 500 meteorites ranging in size from marbles to basketballs or larger reach the earth's surface each year (Meteorite 2009), and estimates for the mass of material that falls on the earth each year range from 37,000 to 78,000 tons. Most of this mass arrives as dust-sized particles (Cornell University 2009). Another study estimates that 0.010kg to 1kg interval -- to between 2,900 and 7,300 kg/yr, or 18,000 to 84,000 meteorites bigger than 0.010kg -- fall on the earth per year (Bland, et al 1996).

Serious attention has been given to possible impacts since Comet P/Shoemaker-Levy 9 (SL9) struck Jupiter on 16-22 July 1994 (Shoemaker-Levy 2011). The largest fragment, "G," which was up to 5km across hit on July 18 and produced an explosion estimated to be equivalent to 6 million megatons of TNT (600 times the world’s nuclear arsenal). The impact of SL9 inspired more diligent attention to the possibility that an asteroid could also cause an ELE on Earth (Grossman 2009). In July 2009 a scar approximately the size of Earth was observed on Jupiter, hinting that another major impact had happened on the same planet almost exactly fifteen years after the impact of SL9 (Madrigal 2009). Had the same object hit Earth, it would have caused catastrophic damage to human civilization. The general public began paying more attention when NASA predicted 40m long asteroid 367943 Duende would nearly miss the earth on 15 February 2013, but on the same day an unknown, unrelated 17m meteorite entered the atmosphere above Chelyabinsk, Russia and caused a lot of damage and personal injury (Chelyabinsk meteor 2014). The Chelyabinsk meteorite is suspected to have broken off the two-kilometer wide Near Earth Asteroid (86039) 1999 NC43, which eventually may have a much larger threat of impact. The Near Earth Asteroid Rendezvous (NEAR) project has been surveying near-earth objects and recommending to world leaders methods for deflecting or destroying dangerous earth-crossing asteroids. Near Earth Asteroids (NEA) are asteroids whose orbit intersects earth's orbit.

It was found that the consequences of a major impact event to civilization would be so costly that surveys must be continued and Near Earth Objects monitored (Yeomans 2013, p122). It is estimated that there are around a thousand NEA asteroids over 2km diameter. Asteroids up to 0.1km diameter explode in the sky, like the Tunguska meteor in 1908 that flattened forests for miles (Tunguska event 2011), due to pressure differences at the top and bottom of the object. Anything larger than that will impact the earth and cause a crater. As late as 2009 in the NEAR program, more than 80 percent of the asteroids 1km in diameter and greater have been surveyed (Yeomans 2009), but few asteroids in the smaller 0.1-1.0km range have been found. These smaller objects probably cannot be spotted far in advance of the impact, perhaps even up until the time of the event, like the Chelyabinsk meteor. Recent data estimates that there are "4,700 ± 1,500 potentially hazardous asteroids with a diameter greater than 100 meters. As of 2012, an estimated 20 to 30 percent of these objects have been found" (Potentially hazardous object 2014). Unfortunately an asteroid the size of a small garage could destroy a city. This is quite alarming, meaning that 70-80 percent of the 0.1-1.0km range asteroids, many well within the definition for an ELE, could hit with little or no advance warning. The probable frequency of an impact can be calculated based on the size of the potential impactor. Table 7 shows ranges of probable impactor sizes, impact energy, crater diameter, and impact frequency (Marcus, Melosh & Collins 2010). NEOs passing close to Earth are listed on the NASA Near Earth Object Program website (NEO Close 2015). Risk tables are also listed on the site (NEO Sentry 2015). Though no known impacts are imminent, several close calls and possible distant future impacts have been identified.

Table 7: NEA probable impact frequency (from Marcus, et al 2010)

Impactor diameter	Kinetic energy at atmospheric entry	Impact energy	Crater diameter	Average frequency
100 m (330 ft)	47 Mt	38 Mt	1.2 km (0.75 mi)	5,200 years
130 m (430 ft)	103 Mt	64.8 Mt	2 km (1.2 mi)	11,000 years
150 m (490 ft)	159 Mt	71.5 Mt	2.4 km (1.5 mi)	16,000 years
200 m (660 ft)	376 Mt	261 Mt	3 km (1.9 mi)	36,000 years
250 m (820 ft)	734 Mt	598 Mt	3.8 km (2.4 mi)	59,000 years
300 m (980 ft)	1,270 Mt	1,110 Mt	4.6 km (2.9 mi)	73,000 years
400 m (1,300 ft)	3,010 Mt	2,800 Mt	6 km (3.7 mi)	100,000 years
700 m (2,300 ft)	16,100 Mt	15,700 Mt	10 km (6.2 mi)	190,000 years
1,000 m (3,300 ft)	47,000 Mt	46,300 Mt	13.6 km (8.5 mi)	440,000 years

The unfortunate thing about NEAs is that they all will impact earth, eventually -- guaranteed. Whether that impact is 10 years from now or 10 million years is not clear, but it is estimated that "regional devastation to human settlements unprecedented in human history -- or a major tsunami -- occur on average around once per 10,000 years" (Potentially hazardous object 2014), and 91 deaths on average are annually attributed to asteroid impacts, or meteorites (National Research Council 2010). The Nuclear Test Band Treaty Organization (NTBTO) recently reported that since the year 2000 their instruments have detected 26 nuclear-level asteroid impacts, some 40 times more powerful than the bomb that destroyed Hiroshima (Amos 2014). Fortunately all these blasts have occurred in remote locations or in the upper atmosphere, but the frequency of these high-powered impacts should come as a warning. Knowing that NEAs will all eventually impact Earth, the four billion year window tightens down to a hundred thousand year window.

C. Hundred Year Window

The advance allocation of technical resources in order to stave off disaster has common local application. Frequent events, such as earthquakes, tornadoes, tsunami, volcanoes, wildfires, hurricanes, storms and droughts are a reminder to build stronger buildings, develop storm watch systems, erect higher sea walls, and keep storm runoff in reservoirs so the water will be there when it is needed. The countries that pay attention, that have greater vision, always fare better than those that didn't allocate resources in advance. On 22 March 2014 a major landslide occurred east of Oso, Washington, causing many deaths in the area (Oso Mudslide 2014). The deaths can be attributed to ignorance of the ground conditions. In contrast, scientists were warned about impending landslides at the Bingham Canyon Kennecott Copper Mine on 10 April 2013 and 11 September 2013 due to electronic monitoring equipment, resulting in no deaths (Bingham Canyon Mine 2014). It has been pointed out that if monitoring technology had been available in the Oso area, there would have been no casualties (Petley 2014; Doughton 2014).

In another example, on 23 July 2013 two massive clouds of plasma exploding out from the sun barely missed hitting Earth. Solar flares such as these are powerful enough to destroy every electrical device in their path, including motors, computers, automobile electronics, appliances, communication networks, and power grids -- enough to shut down the world economy for years. The last time such an occurrence happened was in September 1859, when a plasma cloud directly hit Earth and caused telegraph systems to catch on fire. The 1859 event became known as the Carrington Event, and is not well known because the economies of the time were not so dependent on electrical equipment. Scientists have computed that there is a 12% chance that a Carrington-class storm could directly hit Earth in the next 10 years (Baker, et al, 2014). A Carrington-class event of this magnitude could cause outages and distractions that would reallocate resources away from space development, perhaps for decades to come. Would a space program with so much lost momentum recover?

Nature is not the only destructive force that could cause Extinction Level Events. With the prevalence of exoplanets the Drake Equation illustrates the possibility of untold billions of habitable worlds (SETI 2014). However, no advanced technological alien race has ever been found, leading to what is known as the Fermi Paradox (Fermi Paradox 2015) -- why are there not advanced space-faring civilizations visiting Earth all the time? One possible explanation for the Fermi Paradox is that it may be more likely that a single planet-bound species could destroy themselves before any natural ELE has a chance to wipe them out, or before they are able to achieve sustainable spaceflight and multi-planet status. In the past, someone bent on destruction had to expend considerable effort to convince others to follow them, then use that influence to invade, usurp, or eliminate his enemies in one-on-one confrontations. Even great battles and mass invasions were accomplished through many little instances of hand-to-hand combat played out simultaneously. The only way to come close to mass destruction was to take advantage of stored potential in the environment and through some small action, light the fire that burns down the whole village, start the avalanche that buries the town, or divert the river that floods the valley. Back then, no one had the power to sit safely in a bunker and through the push of a button cause an entire city to be consumed in an instant of nuclear destruction.

Ray Kurzweil and other Transhumanists have warned about a time when computing capability will exceed natural human ability to think and reason, called the "Singularity" (Kurzweil 2005). Artificially intelligent machines may be able to speed up technological development far exceeding what is possible for human engineers, surpassing the gains predicted by Moore's Law (Moore's Law 2013) in a feedback loop that continually improves its capacity out of human reach. Without venturing into whether an artificial intelligence could be so alien from us that the human values, ethics, and morality would not apply, as machines become more and more networked in a network of things (Internet of Things 2013), malicious code may be found taking over common objects similar to what we see in computers. Recently it was found that a smart refrigerator had been hacked to send out 750,000 spam emails (Bort 2014). Highly networked machines could open doors to greater productivity, but out of control may be another means by which the human race could destroy itself.

Another way Homo Sapiens could rush their own destruction may be through simulation. More and more scholarly work has been done questioning whether the world is already a simulation (Simulation Hypothesis 2014). As some physicists begin to advocate a model of the universe where the fundamental forces are exchanges of information rather than energy (Wiener 1948; Wolfram 2002), it has been proposed that the world may consist of simulations (Bostrom 2003). One researcher proposed how to tell if the world is a virtual reality (Whitworth 2008). Another team has explored detailed physical constraints on the universe in order for it to be considered a simulation (Beane, Davoudi, Savage 2012). The conclusion is that it might be possible to discover evidence of a simulation, should that be the case. Whether or not the evidence of a simulation can be found, perhaps the attractiveness of a completely immersive virtual reality might prove too tempting and distracting to allow a space-faring civilization to emerge. Geoffrey Miller, evolutionary psychologist wrote, "I suggest a different, even darker solution to Fermi's Paradox. Basically, I think the aliens don't blow themselves up; they just get addicted to computer games. They forget to send radio signals or colonize space because they're too busy with runaway consumerism and virtual-reality narcissism. They don't need Sentinels to enslave them in a Matrix; they do it to themselves, just as we are doing today" (Miller 2006).

With the programmability of biological cells, another potential threat emerges -- the possibility of engineering invasive viruses and microorganisms. Not only will it soon be possible to engineer artificial organisms that are beneficial -- oil cleanup, processing waste, curing cancer, gene therapy, terraforming, etc. -- but devious persons may be able to create malicious, aggressive enemies invisible to the naked eye. Scientists, realizing the tremendous potential for mayhem caused by poorly engineered organisms called for a moratorium on research for recombinant DNA in 1975, and convened a conference to establish protocols for research. Through guidelines established at what became known as the Asilomar Conference (2014), research on genetic engineering now proceeds in supposedly safe, contained laboratory environments. One potentially useful technology that could also prove destructive if ethics are ignored is gene drives. Gene drives are where inheritance of particular genes are stimulated in order to alter entire populations of organisms in a desired direction. Again, scientists have warned that regulatory gaps must be filled before gene drives could be used in the wild (Esvelt, et al 2014; Oye, et al, 2014). Hawking once said, "In the long term I am more worried about biology. Nuclear weapons need large facilities, but genetic engineering can be done in a small lab. You can't regulate every lab in the world. The danger is that either by accident or design, we create a virus that destroys us" (Highfield 2001).

There are numerous other ways the human race could drive themselves to extinction through mistakes, malicious management of technology, or shortsightedness. Drexler (1986) warned about the mismanagement of nanotechnology. Environmental problems, climate change, and other situations where technology may upset delicate balances may also contribute to an early demise of the human race. It might also be unwise for world populations to continue spending $312 billion a year on recreation, $76 billion a year on cosmetics, $97.5 billion per year on tobacco and alcohol products (Consumer Expenditures 2013), $49 billion per year on lottery tickets (Lottery 2012), or $125 billion per year on gambling (Bazelon, et al 2010) instead of using the funds on worthwhile lasting investments. Would it be possible to keep spending on entertainment and still invest wisely? Of course it is (zero gravity football? Quiddich, anyone?)! But it will be important to admit where the long-range priorities ought to be and plan accordingly. Encourage forms of entertainment that fund the future.

Finally, there have been fears about runaway population growth that could choke the planet and spread resources thin. Can overpopulation and strain on resources become a problem? The term "overpopulate" is subjective and hard to quantify -- the correct way to think of it may be management of resources befitting population size. Poor resource management will result in a culture that seems overpopulated. More likely, population pressures may never get to the point where they endanger the planet in the long run, but would tend to pressure humanity to reach out and embrace space-based resources. Larger populations ideally create larger tax bases, which in turn provide larger funding pools. A more alarming trend may be underpopulation, or the loss of human capital. The community has a vested interest in the management of human capital, without which the community crumbles, and resource management infrastructures fall behind. A robust system of human capital management insures that fertility rates adequately replace and sustain the current work force, by bearing children and raising them through to productive adulthood. If the human capital management system doesn't work properly, the fraction of non-productive members of a community will increase and strain its resources, which must be recovered by the productive individuals. This harms those individuals that must do the extra work to make up for what others are not capable or willing to do. It has been shown that, in order to keep replacement of labor forces sustainable, each person has an obligation to bear 1.05 children and raise them to productive adulthood -- which becomes 2.1 children per couple (Last 2013). Perhaps one of the quickest ways to hinder a space development program might be to lower fertility, reduce the size of the labor pool, decrease the tax base, and convince the world to make do with the resources available on this planet.

D. 50 Year Window

In one interview, the famous physicist Professor Stephen Hawking sets his deadline for when we must become a spacefaring civilization, "I don't think the human race will survive the next thousand years, unless we spread into space. There are too many accidents that can befall life on a single planet" (Highfield 2001). In a later interview, Hawking tightens the deadline down to two hundred years, "If we can avoid disaster for the next two centuries, our species should be safe, as we spread into space" (Parry 2010). In 1993 cosmologist Richard Gott calculated the probability that the motivation and capacity to engage in space travel may only be with us for another 32 years, which puts a critical deadline at the year 2025 (Gott 1993).

Is there any merit to Gott's and Hawking's concern? Taking a detailed look at world energy production, use, and projections (Energy Outlook 2013; World Energy Consumption 2014), worldwide energy consumption was 143,851 terawatt hours, with 81.2% being from fossil fuels. The world's critical defense, transportation, and food production systems depend on cheap, abundant oil (Roberts 2008). But there are those who warn the world of an impending "Peak Oil", where production reaches its maximum capacity and begins to run out (Deffeyes 2001; Peak Oil 2014). Some say the Oil Peak has already arrived, covered up by market fluctuation and oil prices that dampen consumption that would otherwise occur if oil were cheaper, while others say it is still decades away (Miller & Sorrell 2013). Optimists say there may be 50% more oil supply than is assumed by the Peak Oil advocates, but at the most that would only buy the world a few more years (Appenzeller 2004). According to Appenzeller, oil reserves in 2004 were 1,250 billion barrels, with a depletion rate of 23.3 billions of barrels a year (Oil Depletion 2014). At that rate the world's oil supply will be depleted by 2057.

Other experts are not so gloomy in their predictions, but agree that oil is running out. According to peer-reviewed research (Owen, et al 2010), the reality is that there will be plenty of oil still in the ground, but it will get more and more expensive to extract what's left. More and more creative, and possibly controversial, means will have to be devised, such as "fracking", etc. During the transition period higher costs for extracting oil will make alternative energy more attractive, but consumer behaviors will need to change and there will have to be mitigation of environmental and social costs that will likely be upsetting to our current way of life. Once oil has run dry or become too expensive to extract, by the numbers nuclear and renewable energy could take up the slack for continually increasing world demand for energy. Where oil, coal, and natural gas provided worldwide 116,835 terawatt hours of energy, solar power alone has an ultimate annual potential to provide 438,000 terawatt hours, with even more potential from geothermal energy at 1,400,000 terawatt hours (World Energy Consumption 2014).

Unfortunately, trying to replace fossil fuels to feed the world's energy needs will be difficult to do with renewable energy, even if the equivalent energy levels are technically available. In order to complete major engineering projects such as space colonization, any nation or private entity will need a robust, high density, storable energy economy that renewable energy has yet to deliver. A hydrogen economy is not very practical because the minus 252.87 deg C boiling point of hydrogen leads to difficulty of storage -- the fuel will boil off faster than it is practical to use in a sustainable way without expensive and complex cryogenic storage systems. Methane with a boiling point of -161 deg C has been proposed as a better option for condensing and storage (Zubrin 2007; Olah, et al 2009), but the difficulties of transferring over to a bulk methanol storage and distribution infrastructure system to replace over 80 percent of the world's energy needs will be a daunting, if not economically impractical prospect.

For these reasons, our short window for establishing an infrastructure for obtaining space-based energy and resources may be only five decades away, once the easy earth-based resources are gone. If we don't dedicate our national and world resolve to attaining limitless extraterrestrial resources within 50 years, our chances for doing so may forever pass us by and doom our human race to extinction -- the extreme challenges of setting up alternate energy economies will so tax our efforts and set back our vision that we may never again be able to build up the momentum to reach for the stars.

IV. Conclusions

From published sources, an academic estimate was made for what it might take to put a minimal permanent settlement on Mars for preserving the human gene pool. The calculations showed there would need to be over 995,000kg of mass that would take 75 launches of the Space Launch System, or 184 Falcon Heavy launches, at a cost of 162 billion dollars. With NASA's current budget, such a program would take from 22 to 26 years to accomplish. Through a study of available literature, it was found that the human race may only have a small window of 30-50 years in which to become a space-faring species, or forever be content with being a single-planet species subject to extinction. In order to be serious about the survival of the human race and not get distracted, it will be important to make it a priority to accelerate space development for unlimited resources and human survival. It is time to act now, and stop thinking that future generations will take up the cause.

Acknowledgments

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

References

AFJ Abercromby; ML Gernhardt; J Jadwick (2012). Evaluation of dual multi-mission space exploration vehicle operations during simulated planetary surface exploration. Acta Astronautica, vol 90, pp203-214.

B Aldrin; R Tumlinson (2006). Apollo 11 Anniversary: Heroes, Quests and Space. *Space.com / Ad Astra Online*, 20 July 2006. Retrieved 29 July 2015 from http://www.space.com/2648-apollo-11-anniversary-heroes-quests-space.html

J Amos (2014). Asteroid Impact Risks 'Unappreciated'. (Posted 22 Apr 2014), in *BBC News*: Science & Environment. Retrieved 23 Apr 2014, from http://m.bbc.com/news/science-environment-27039285

T Appenzeller (2004). End of Cheap Oil. *National Geographic Online Extra*. Retrieved 31 Aug 2014, from http://ngm.nationalgeographic.com/ngm/0406/feature5/fulltext.html

N Armstrong (1999). *Apollo 11 30th Anniversary Press Conference*, 16 July 1999, Kennedy Space Center. Retrieved 29 July 2015 from: http://history.nasa.gov/ap11ann/pressconf.htm

Asilomar Conference (2014). Asilomar Conference on Recombinant DNA. In *Wikipedia, The Free Encyclopedia*. Retrieved 2 Aug 2014, from http://en.wikipedia.org/wiki/Asilomar_Conference_on_Recombinant_DNA

D Baker; X Li; A Pulkkinen; C Ngwira; M Mays; A Galvin; K Simunac (2013). A Major Solar Eruptive Event in July 2012: Defining Extreme Space Weather Scenarios. *Space Weather*, Volume 11, Issue 10, Oct 2013, pp585-591. doi:10.1002/swe.20097

C Bazelon; K Neels; P Seth (2010). *Beyond the Casino Floor: Economic Impacts of the Commercial Casino Industry*. The Brattle Group for the American Gaming Association. Retrieved 10 Oct 2014, from http://www.americangaming.org/sites/default/files/uploads/docs/final_final_brattle_study_2-3-12.pdf

Bingham Canyon Mine (2014). In *Wikipedia, The Free Encyclopedia*. Retrieved 23 Apr 2014, from http://en.m.wikipedia.org/wiki/Bingham_Canyon_Mine

A Bonanno; H Schlattl; L Paternò (2008). The age of the Sun and the relativistic corrections in the EOS. *Astronomy and Astrophysics*, Volume 390, Number 3, pp1115–1118. doi:10.1051/0004-6361:20020749

J Bort (2014). For The First Time, Hackers Have Used A Refrigerator To Attack Businesses. (Posted 16 Jan 2014), in *Business Insider Tech Enterprise*. Retrieved 21 Jan 2014, from http://www.businessinsider.com/hackers-use-a-refridgerator-to-attack-businesses-2014-1

N Bostrom (2003). Are You Living in a Computer Simulation? *Philosophical Quarterly*, Vol 53, No 211, pp243-255. Also available at http://www.simulation-argument.com/simulation.html

B Bova (1981). *The High Road*. Houghton Mifflin.

S Beane; Z Davoudi; M Savage (2012). Constraints on the Universe as a Numerical Simulation. arXiv:1210.1847v2

M Beech (2009). *Terraforming: The Creating of Habitable Worlds*. New York, New York, USA: Springer.

P Bland; T Smith; A Jull; F Berry; A Bevan; :S Cloudt; C Pillinger (1996). The Flux of Meteorites to the Earth Over the Last 50,000 Years. *Monthly Notices of the Royal Astronomical Society*, Volume 283, pp551-565.

Consumer Expenditures (2013). *Consumer Expenditure Survey*. Bureau of Labor Statistics, United States Department of Labor. Retrieved 10 Oct 2014, from http://www.bls.gov/cex/2013/combined/region.pdf

A Chaikin (2001). Meeting of the Minds: Buzz Aldrin Visits Arthur C Clarke. Interview on *space.com*. Retrieved 29 July 2015 from http://web.archive.org/web/20010302082528/http://www.space.com/peopleinterviews/aldrin_clarke_010227.html

PK Chapman (1978). Review of GK O'Neil (1977) "The High Frontier: Human Colonies In Space", RD Johnson & C Holbrow (1977) "Space Settlements: A Design Study", TA Heppenheimer (1977) "Colonies in Space", and F Golden (1977) "Colonies in Space: The Next Giant Step". *Physics Today*, Volume 31, Issue 9, pp69-70.

Chelyabinsk meteor (2014). In *Wikipedia, The Free Encyclopedia*. Retrieved 20 Jan 2014, from http://en.m.wikipedia.org/wiki/Chelyabinsk_meteor

AC Clarke (1960). *Interplanetary Flight: An Introduction to Astronautics*, Chapter 10, p127. New York, New York, USA: Harper & Row Publishers. Originally published 1950 by Temple Press Limited, London, UK.

AC Clarke; I Macauley (2001). *Greetings, Carbon-Based Bipeds!: Collected Essays*, 1934-1998, p104. New York, NY, USA: Macmillan.

P Collins; A Autino (2008). What the Growth of a Space Tourism Industry Could Contribute to Employment, Economic Growth, Environmental Protection, Education, Culture and World Peace. Plenary Session of the *International Academy of Astronautics' 1st Symposium on Private Human Access to Space*, held at Arcachon, France, 25-28 May 2008.

Cornell University (2009). How Many Meteorites Hit Earth Each Year? (Posted 2003), in *Curious About Astronomy? Ask An Astronomer*. Retrieved 25 Sep 2009, from http://curious.astro.cornell.edu/question.php?number=470

P Davies (2004). Life (and Death) on Mars. *The New York Times*, Opinion, 15 Jan 2004. Retrieved 29 Jul 2015 from: http://www.nytimes.com/2004/01/15/opinion/15DAVI.html

K Deffeyes (2001). *Hubbert's Peak: The Impending World Oil Shortage*, revised edition. Princeton University Press.

S Doll; P Eckart (1999). Chapter 17: Environmental Control and Life Support Systems (ECLSS), pp539-573. In W Larson & L Pranke (eds), *Human Spaceflight: Mission Analysis and Design*. McGraw Hill.

S Doughton (2014). Monitoring Can Warn Of Impending Slides -- At A Cost. (Posted 3 Apr 2014), in *The Seattle Times*: Local News. Retrieved 23 Apr 2014, from http://seattletimes.com/html/localnews/2023296634_mudslidemonitorxml.html

H Downs (2008). Hugh Downs: "Ships for the Stars". *Ad Astra*, Volume 20, Number 3, Fall 2008, p44.

KE Drexler (1986). *The Engines of Creation: The Coming Era of Nanotechnology*. New York, New York, USA: Doubleday.

KA Ehricke (1981). The Extraterrestrial Imperative. *Futures*, Volume 13, Issue 2, pp107-114.

Energy Outlook (2013). *International Energy Outlook 2013*, DOE/EIA-0484(2103). Department of Energy: US Energy Information Administration.

K Esvelt; A Smidler; F Catteruccia; G Church (2014). Concerning RNA-guided Gene Drives for the Alteration of Wild Populations. *eLife*. doi:10.7554/eLife.03401

Federal Budget (2013). 2013 United States Federal Budget. In *Wikipedia, The Free Encyclopedia*. Retrieved 10 Oct 2014, from http://en.m.wikipedia.org/wiki/2013_United_States_federal_budget

Fermi Paradox (2015). In *Wikipedia, The Free Encyclopedia*. Retrieved 30 July 2015, from http://en.m.wikipedia.org/wiki/Fermi_paradox

M Fogg (1995). *Terraforming: Engineering Planetary Environments*. Warrendale, Pennsylvania, USA: Society of Automotive Engineers.

I Franklin (1980). Evolutionary Change in Small Populations. In M Soule & B Wilcox (eds) (1980) *Conservation Biology, An Evolutionary-Ecological Perspective*. Sunderland, Massachusetts, USA: Sinauer. ISBN: 0878938001

R Freitas; W Gilbreath (1980). Chapter 5: Replicating Systems Concepts: Self-replicating Lunar Factory and Demonstration. In R Freitas & W Gilbreath (eds), *Advanced Automation for Space Missions*. Proceedings of the 1980 NASA / ASEE Summer Study (Conference Publication 2255), pp189-336. Washington DC: NASA Scientific and Technical Branch.

R Freitas; R Merkle (2004). *Kinematic Self-replicating Machines*. Georgetown, Texas, USA: Landes Bioscience.

RB Fuller (1964). The Prospect for Humanity. *Saturday Review*, 29 Aug 1964, pp43-45.

RB Fuller (1969). *Operating Manual for the Spaceship Earth*. Retrieved 29 July 2015 from http://designsciencelab.com/resources/OperatingManual_BF.pdf

ML Gernhardt; AFJ Abercromby (2008). Health and Safety Benefits of Small Pressurized Suitport Rovers as EVA Surface Support Vehicles. AsMA 2008 Annual Scientific Meeting. Boston, MA, USA: Aerospace Medical Association.

JR Gott (1993). Implications of the Copernican Principle For Our Future Prospects. *Nature*, Vol 363, 27 May 1993, pp315-319.

L Grossman (2009). Jupiter Sports New 'Bruise' from Impact. *New Scientist*, online edition. Retrieved 1 Aug 2009 from: http://www.newscientist.com/article/dn17491-jupiter-sports-new-bruise-from-impact.html

L Guerra; R Shishko (1999). Chapter 29: Estimating the Cost of Crewed Space Systems, pp933-960. In W Larson & L Pranke (eds), *Human Spaceflight: Mission Analysis and Design*. McGraw-Hill.

A Hanford (2004). Advanced Life Support Baseline Values and Assumptions Document NASA/CR-2004-208941. National Aeronautics and Space Administration.

P Harris (2010). Elon Musk: 'I'm Planning to Retire On Mars'. The Observer, *The Guardian*, 1 Aug 2010. Retrieved 29 July 2015 from http://www.theguardian.com/technology/2010/aug/01/elon-musk-spacex-rocket-mars

R Heinlein (1970). *I Will Fear No Evil*, Chapter 26. Penguin Putnam books.

TA Heppenheimer (1979). *Toward Distant Suns*. Ballantine Books.

R Highfield (2001). Colonies in Space May Be Only Hope, Says Hawking. *The Telegraph*, 16 Oct 2001. Retrieved 1 Sep 2014, from http://www.telegraph.co.uk/news/uknews/1359562/Colonies-in-space-may-be-only-hope-says-Hawking.html

AS Howe (2015). A Modular Habitation System for Human Planetary and Space Exploration (ICES-2015-4). *45th International Conference on Environmental Systems (ICES2015)*, Belleview, Washington, USA, 12-16 July 2015. Lubbock, Texas, USA: Texas Tech University.

AS Howe; B Wilcox; C Mcquin; D Mittman; J Townsend; R Polit-Casillas; T Litwin (2014). Modular Additive Construction Using Native Materials. *Proceedings of the Fourteenth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth & Space 2014)*. St Louis, Missouri, 27-29 Oct 2014. Reston, Virginia, USA: American Society of Civil Engineers.

AS Howe; B Wilcox; C McQuin; J Townsend; R Rieber; M Barmatz; J Leichty (2013). Faxing Structures to the Moon: Freeform Additive Construction System (FACS) (AIAA2013-5437). *AIAA Space 2013 Conference & Exhibition*. San Diego, California, USA, 10-12 Sep 2013. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

BM Hubbard (1977). Why Space Now? *L-5 News*, Volume 2, Number 1, January 1977.

Internet of Things (2013). In *Wikipedia, The Free Encyclopedia*. Retrieved 30 Dec 2013, from http://en.m.wikipedia.org/wiki/Internet_of_things:

J Koebler (2015). DARPA: We Are Engineering the Organisms That Will Terraform Mars. *Motherboard*, 24 June 2015. Retrieved 30 July 2015 from: http://motherboard.vice.com/read/darpa-we-are-engineering-the-organisms-that-will-terraform-mars

R Kurzweil (2005). *The Singularity Is Near*. New York, New York, USA: Viking Penguin.

J Last (2013). *What to expect when no one's expecting*. New York, New York, USA: Encounter Books.

J Lewis (1996). *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets*. New York, New York, USA: Basic Books (Perseus Books).

Lottery (2012). *Lottery Sales and Transfers*. North American Association of State and Provincial Lotteries. Retrieved 10 Oct 2014, from http://www.naspl.org/index.cfm?fuseaction=content&menuid=17&pageid=1025

A Madrigal (24 July 2009). Hubble Snaps the Sharpest Image Yet of Jupiter Impact. *Wired Science*. Retrieved 1 Aug 2009 from: http://www.wired.com/wiredscience/2009/07/hubble-snaps-sharpest-image-yet-of-jupiter-impact/

R Marcus; HJ Melosh; G Collins (2010). *Earth Impact Effects Program*. Imperial College London / Purdue University. http://impact.ese.ic.ac.uk/ImpactEffects/ As referenced in Impact Event (2015). In *Wikipedia: The Free Encyclopedia*. Retrieved 30 July 2015 from: https://en.wikipedia.org/wiki/Impact_event. Table calculated with solution using 2600kg/m^3, 17km/s, 45 degrees.

Meteorite (2009). In *Wikipedia, The Free Encyclopedia*. Retrieved 25 Sep 2009, from http://en.m.wikipedia.org/wiki/Meteorite

M Michaud (1979). Improving the Prospects for Life in the Universe. In WA Gale (ed), American Association for the Advancement of Science (AAAS) Selected Symposia SS(NS)-31, *Life in the Universe: The Ultimate Limits to Growth*, pp107-117. Boulder, Colorado, USA: Westview Press.

G Miller (2006). Runaway Consumerism Explains the Fermi Paradox. *The Edge* Annual Question 2006: "What is your dangerous idea?". Retrieved 20 Jul 2015 from: http://edge.org/q2006/q06_print.html#miller

R Miller; S Sorrell (2013). The Future of Oil Supply. *Philosophical Transactions of The Royal Society: Mathematical, Physical & Engineering Sciences*, Volume 372, Number 2006, 27 pages.

Moore's Law (2013). In *Wikipedia, The Free Encyclopedia*. Retrieved 30 Dec 2013, from http://en.m.wikipedia.org/wiki/Moore's_law

NASA Agency Financial Report (2013). *FY 2013 Agency Financial Report*. National Aeronautics and Space Administration.

National Research Council (2010). *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*. Washington, DC, USA: National Academic Press.

M Nelson; N Pechurkin; J Allen; L Somova; J Gitelson (2009). Chapter 11: Closed Ecological Systems, Space Life Support and Biospherics, pp517-565. In L Wang, et al (eds), *Handbook of Environmental Engineering*, Volume 10: Environmental Biotechnology. New York, New York, USA: Humana Press. doi:10.1007/978-1-60327-140-0_11

NEO Close (2015). *NEO Earth Close Approach list*. NASA Jet Propulsion Laboratory Near Earth Object Program. Retrieved 30 July 2015 from: http://neo.jpl.nasa.gov/ca/

NEO Sentry (2015). *Sentry Risk Table*. NASA Jet Propulsion Laboratory Near Earth Object Program. Retrieved 30 July 2015 from: http://neo.jpl.nasa.gov/risks/

H Oberth (1957). *Man Into Space: New Projects for Rocket and Space Travel*, Chapter VIII, p167. New York, New York, USA: Harper & Brothers.

Oil Depletion (2014). In *Wikipedia, The Free Encyclopedia*. Retrieved 31 Aug 2014, from http://en.m.wikipedia.org/wiki/Oil_depletion

G Olah; A Goeppert; G Surya Prakash (2009). *Beyond Oil and Gas: The Methanol Economy*. Fed Rep of Germany: Wiley-VCH.

GK O'Neill (1978). *The High Frontier*. New York, New York, USA: Bantam Dell Doubleday Publishing Group.

Oso Mudslide (2014). In *Wikipedia, The Free Encyclopedia*. Retrieved 23 Apr 2014, from http://en.m.wikipedia.org/wiki/2014_Oso_Mudslide

N Owen; O Inderwildi; D King (2010). The Status of Conventional World Oil Reserves -- Hype or Cause For Concern? *Energy Policy*, Volume 38, Issue 8, pp4743-4749. doi:10.1016/j.enpol.2010.02.026

K Oye; K Esvelt; E Appleton; F Catteruccia; G Church; T Kuiken; S Lightfoot; J McNamara; A Smidler; J Collins (2014). Regulating Gene Drives. *Science*, Science Express, Policy Forum, 17 Jul 2014, pp1-4. doi:10.1126/science.1254287

D Parry (2010). Stephen Hawking: Mankind Must Colonise Space or Die Out. *The Guardian*, 9 Aug 2010. Retrieved 1 Sep 2014, from http://www.theguardian.com/science/2010/aug/09/stephen-hawking-human-race-colonise-space

Peak Oil (2014). In *Wikipedia, The Free Encyclopedia*. Retrieved 31 Aug 2014, from http://en.m.wikipedia.org/wiki/Peak_oil

D Petley (2014). The Oso (Steelhead) Landslide In Washington State -- Could It Have Been Foreseen? (Posted 2 Apr 2014), in American Geophysical Union (AGU) Blogosphere, *The Landslide Blog*. Retrieved 23 Apr 2014, from http://blogs.agu.org/landslideblog/2014/04/02/steelhead-landslide-in-washington/

Potentially hazardous object (2014). In *Wikipedia, The Free Encyclopedia*. Retrieved 20 Jan 2014, from http://en.m.wikipedia.org/wiki/Potentially_hazardous_object

J Pournelle (1979). *A Step Farther Out*. Ace Books.

M Rees (2003). *Our Final Hour: A Scientist's Warning*, p181. Basic Books.

P Roberts (2008). Tapped Out. *National Geographic* Feature Article. Retrieved 31 Aug 2014, from http://ngm.nationalgeographic.com/2008/06/world-oil/roberts-text

E Rosen (1965). *Kepler's Conversation With Galileo's Sidereal Messenger (The Sources of Science, No 5)*. New York, New York, USA: Johnson Reprint Corporation.

C Sagan (1980). *Cosmos*, p218. New York, New York, USA: Random House.

C Sagan (1994). *Pale Blue Dot: A Vision of the Human Future in Space*, Chapter 21, p371. New York, New York, USA: Random House, Inc.

J Samenow (2014). How a Solar Storm Two Years Ago Nearly Caused a Catastrophe on Earth. *The Washington Post*, Capital Weather Gang, 23 Jul 2014. Retrieved 2 Aug 2014, from http://m.washingtonpost.com/blogs/capital-weather-gang/wp/2014/07/23/how-a-solar-storm-nearly-destroyed-life-as-we-know-it-two-years-ago/

MT Savage (1994). *The Millennial Project: Colonizing the Galaxy in Eight Easy Steps*. Little, Brown & Co.

Shoemaker-Levy (2011). In *Wikipedia: The Free Encyclopedia*. Retrieved 22 Oct 2011 from: http://en.wikipedia.org/wiki/Comet_Shoemaker-Levy_9

KP Schröder; CR Smith (2008). Distant future of the Sun and Earth revisited. *Monthly Notices of the Royal Astronomical Society*, Volume 386, pp155-163. doi:10.1111/j.1365-2966.2008.13022.x

P Schulte; L Alegret; I Arenillas; JA Arz; PJ Barton; PR Bown; TJ Bralower; GL Christeson; P Claeys; CS Cockell; GS Collins; A Deutsch; TJ Goldin; K Goto; JM Grajales-Nishimura; RAF Grieve; SPS Gulick; KR Johnson; W Kiessling; C Koeberl; DA Kring; KG MacLeod; T Matsui; J Melosh; A Montanari; JV Morgan; CR Neal; DJ Nichols; RD Norris; E Pierazzo; G Ravizza; M Rebolledo-Vieyra; WU Reimold; E Robin; T Salge; RP Speijer; AR Sweet; J Urrutia-Fucugauchi; V Vajda; MT Whalen; PS Willumsen (5 March 2010). The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary. *Science* (AAAS), Volume 327, Number 5970, pp1214–1218. doi:10.1126/science.1177265

SETI (2014). *The Drake Equation*. Retrieved 31 May 2014, from: http://www.seti.org/drakeequation

R Shapiro (1999). *Planetary Dreams: The Quest to Discover Life Beyond Earth*. New York, New York, USA: Wiley.

R Shishko; R Fradet; S Saydam; C Tapia-Cortez; A Dempster; J Coulton (2015). An Integrated Economics Model for ISRU in Support of a Mars Colony. *AIAA Space 2015 Conference & Exhibition*, Pasadena, California, USA, 31 Aug – 2 Sep 2015. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

Simulation Hypothesis (2014). In *Wikipedia, The Free Encyclopedia*. Retrieved 6 Apr 2014, from http://en.m.wikipedia.org/Simulation_Hypothesis

C Smith (2013). Estimation of a Genetically Viable Population for Multigenerational Interstellar Voyaging: Review and Data for Hyperion. *Acta Astronautica*, Volume 97, Apr-May 2014,pp16-29. doi:10.1016/j.actaastro.2013.12.013

Space Launch System (2014). In Wikipedia, The Free Encyclopedia. Retrieved 1 Sep 2014, from http://en.m.wikipedia.org/wiki/Space_Launch_System

SpaceX (2013). *SpaceX Capabilities and Services*. Retrieved 4 July 2014, from http://www.spacex.com/about/capabilities

D Stilwell; R Boutros; J Connolly (1999). Chapter 18: Crew Accommodations, pp575-606. In W Larson & L Pranke (eds), *Human Spaceflight: Mission Analysis and Design*. McGraw-Hill.

Y Tako; R Arai; S Tsuga; O Komatsubara; T Masuda; S Nozoe; K Nitta (2010). CEEF: Closed Ecology Experiment Facilities. *Gravitational and Space Biology*, Volume 23, Number 2, Aug 2010.

CB Thomas (2007). The Space Cowboys, 22 Feb 2007. *Time magazine*, Volume 169, Number 10, 5 March 2007.

Time Magazine (1958). SPACE: Reach for the Stars. *Time magazine*, Volume 71, Number 7, 17 Feb 1958.

Tunguska event (2011). In *Wikipedia, The Free Encyclopedia*. Retrieved 22 Oct 2011, from http://en.m.wikipedia.org/wiki/Tunguska_event

JC Venter (2013). *Life at the Speed of Life: From the Double Helix to the Dawn of Digital Life*. New York, New York, USA: Viking.

W von Braun (1953). A Plea for a Coordinated Space Program. In J Logan (ed). *The Complete Book of Outer Space*. Gnome Press.

Washington Post (2005). NASA's Griffin: 'Humans Will Colonize the Solar System'. *Washington Post*. 25 Sep 2005, pB07.

R Wheeler (2010). Plants for Human Life Support in Space: From Myers to Mars. *Gravitational and Space Biology*, Volume 23, Number 2, pp25-36.

B Whitworth (2008). The Physical World as a Virtual Reality. arXiv:0801.0337

N Wiener (1948). *Cybernetics, or Control and Communication in the Animal and the Machine*. Cambridge, Massachusetts, USA: MIT Press.

BH Wilcox (2012). ATHLETE: A Limbed Vehicle for Solar System Exploration. *IEEE Aerospace Conference*, 3 - 10 Mar 2012, Big Sky, Montana, USA. New York, NY, USA: Institute of Electrical and Electronics Engineers.

BH Wilcox; T Litwin; J Biesiadecki; J Matthews; M Heverly; J Townsend; N Ahmad; A Sirota; B Cooper (2007). ATHLETE: A Cargo Handling and Manipulation Robot for the Moon. *Journal of Field Robotics*, Vol 24, No 5, pp421-434.

S Wolfram (2002). *A New Kind of Science*. Champaign, Illinois, USA: Wolfram Media.

World Energy Consumption (2014). In *Wikipedia, The Free Encyclopedia*. Retrieved 31 Aug 2014, from http://en.m.wikipedia.org/World_energy_consumption

D Yeomans (2009). Chicken Little Was Right! The Sky Is Falling. Lecture given at NASA Jet Propulsion Laboratory, 21 Jan 2009. Notes in possession of A. Scott Howe.

D Yeomans (2013). *Near-Earth Objects: Finding Them Before They Find Us*. ISBN 978-0-691-14929-5. Princeton, New Jersey, USA: Princeton University Press.

R Zubrin (1996). *The Case for Mars*, p303. New York, New York, USA: Touchstone.

R Zubrin (2007). *Energy Victory: Winning the War on Terror by Breaking Free of Oil*. Amherst, New York, USA: Prometheus Books.