Human Factors Issues

for Interstellar Spacecraft

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Abstract

The prospect of interstellar travel challenges many of the common assumptions about long duration manned spaceflight, raising significant issues about how human factors requirements may change for the multigenerational space flight required for interstellar travel. Mission duration is the driving cause for most human factors issues involving isolation, confinement and exposure to weightlessness and radiation. The notion of a self–sustaining, interstellar spacecraft derives largely from the scenario of travelling O'Neillian space settlements. This article reviews this scenario in light of current developments in space human factors research and technology. The discussion concerns mission duration, spacecraft and crew size, human accommodations and requirements for habitability and safety. The human factors issues that emerge include habitability, human–machine interfaces, crew training and selection, "sweat equity" and population growth.

INTRODUCTION: Assumptions about Interstellar Travel

Futurists, philosophers, scientists and science fiction writers have created a complex tissue of scientific theory, reasoned assumptions and outright speculation about the character of interstellar travel. Each of these assumptions and speculations leads to important human factors issues.

The duration of an interstellar mission or migration will define its character more forcefully than any other factor. The most common (and not necessarily compatible) assumptions, distilled from the literature about interstellar missions, are:

1) Exploration of another star system and return to Earth in one lifetime will be possible someday.
2) Early interstellar voyages will be multigenerational emigrations in immense, self–sustaining vehicles based upon proposed space colonies.
3) Spaceflight safety, habitability requirements and social standards on an interstellar vehicle may be essentially the same as today, although perhaps more earth–like.
4) The interstellar travellers must bring a broad economic and vocational base with them to pioneer successfully on a new planet.

The underlying human factors issue for all of these assumptions is what human factors technologies would be appropriate and useful to enhance long term human performance, safety, reliability and social cohesion.

MISSION DURATION

Mission duration drives the human factors issues of a space mission more than any other single factor. Long mission duration compounds and magnifies all the critical aspects of isolation, confinement, social organization, training and decisionmaking. Many authors present only selected values for relativistic time dilation, to support a particular argument. It is essential to present the background to allow comparative analysis about interstellar mission duration.

Special Theory of Relativity

The fourth equation of the Lorentz transformation demonstrates the relationship between velocity and time, namely,

$$t' = \frac{t - \frac{v}{c^2}x}{\sqrt{1 - \frac{v^2}{c^2}}}$$

After a substitution of $^{v}/_{t}$ for x, this equation reduces to

$$t' = t\sqrt{1 - \frac{v^2}{c^2}} \quad .$$

This equation quantifies the concept of time dilation.[1] At velocities approaching the speed of light, time moves slower with respect to a stationary reference frame. Most articles on the subject of interstellar travel pick one or two examples of distance and trip duration, which can often be misleading. For this discussion, it is useful to present a plot of travel times comparing travel times with and without relativistic effects.

Figure 1 illustrates a plot of the time to travel from Earth to Proxima Centauri expressed as a function of the fraction of the speed of light, c. Figure 1 illustrates the effect of time dilation on a four light-year voyage, approximately the distance to Proxima Centauri, the nearest star (after the sun). The following discussion explains why a speed of .05c is the threshold of human factors feasibility for this journey.

Figure 2 shows an enlarged detail of the higher percentage values of the speed of light. At about one-half the speed of light, a traveler would save approximately one year of trip time due to relativistic effects. Relativistic effects become much more pronounced at greater than .95c. Neither Figure 1 nor Figure 2 include acceleration and deceleration time, just constant velocity. The perception of time dilation would occur upon the return of a starship to Earth, when more time has elapsed for the people on Earth than for the crew.

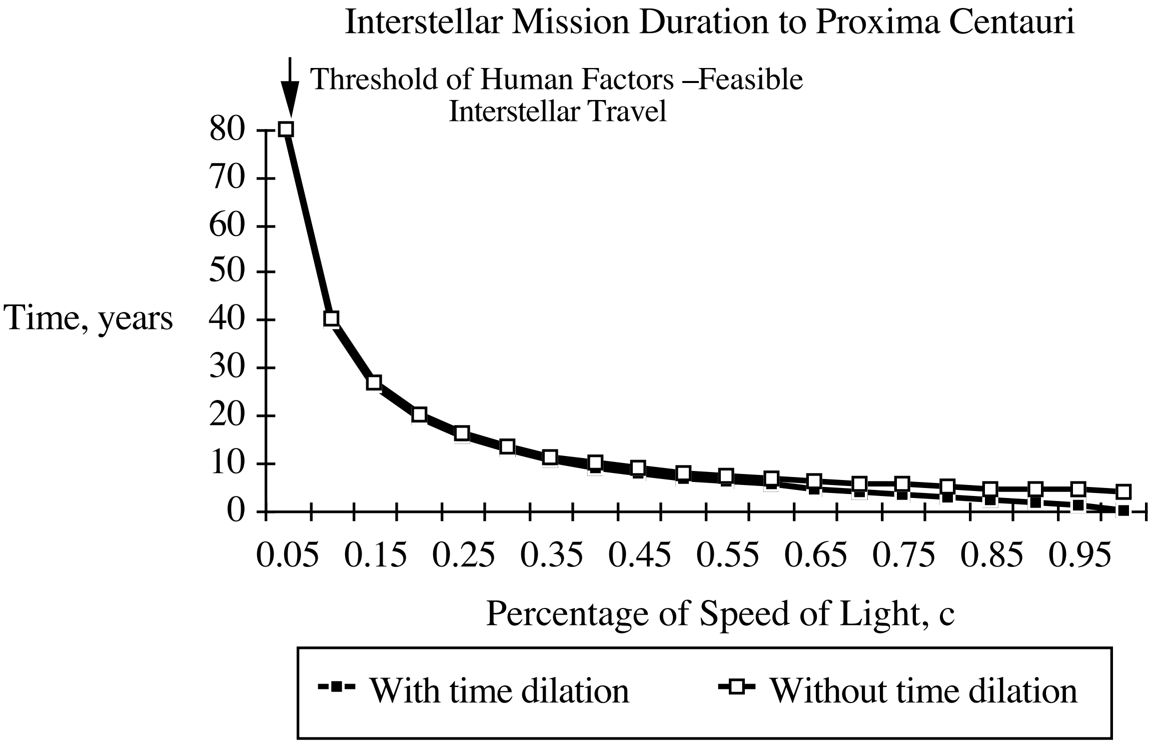


Figure 1. Constant velocity travel time from Earth to Proxima Centauri expressed as a percentage of the speed of light, c.

Iain Nicolson uses values of less than .01c to designate a “space ark” scenario (a travelling O'Neillian “Island One” Space Colony in which approximately 10,000 people live for generations); values between .01c and .05c for a “fast starship” that makes a one way journey possible within a human's lifetime; and values “near the speed of light” to indicate “relativistic spaceflight.” He suggests .99c to illustrate a vehicle in which round trip journeys to star systems beyond Proxima Centauri theoretically become possible.[2]

Louis Friedman points out that to travel the four light years from earth to Proxima Century in 100 years, a spacecraft would need to achieve .04c with the average speed of 29 million miles/hour, including acceleration and deceleration time. Friedman advocates the use of solar sails for interstellar travel, but recognizes that a solar sail voyage to Proxima Centauri could take about 6,600 years,[3] a longer period than recorded human history.

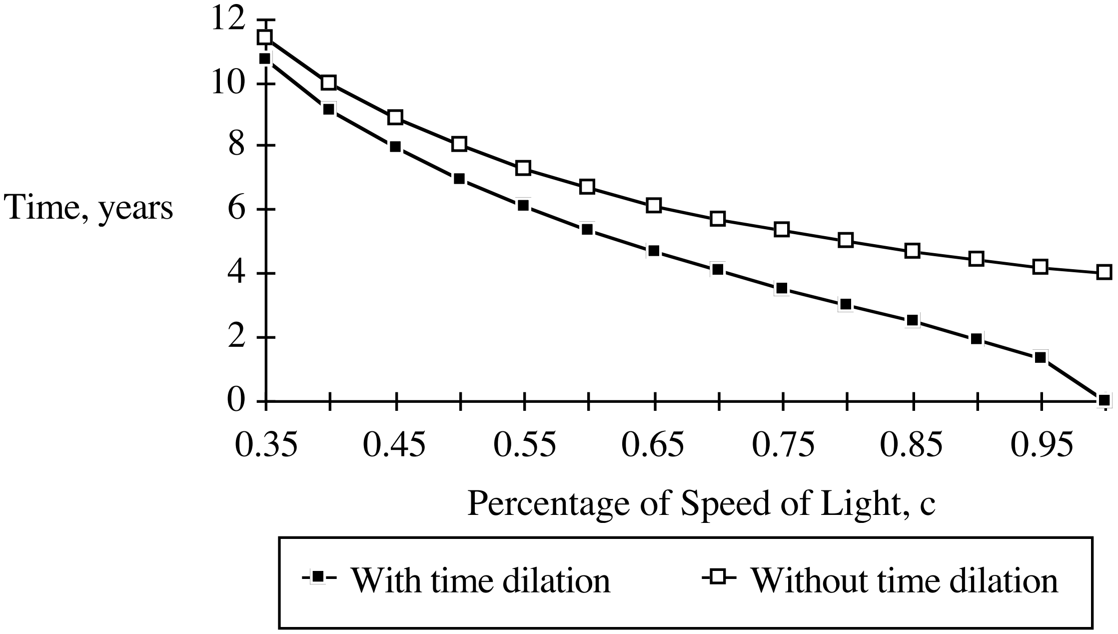


Figure 2. Detail of travel time plots to Proxima Centauri with and without the relativistic effects of time dilation.

Appropriate and Feasible Mission Durations

Given the range of possibilities described by Friedman, Nicolson and many others, it is essential to evaluate the different classifications of mission duration. These classifications may be described as the millennial space ark, the multigenerational one–way and the relativistic round trip. The time frame for each classification implies a profoundly different type of spacecraft and crew society to operate it.

A "Space Ark" might use solar sails or conventional propulsion to travel at relatively slow speeds, with trip time measured in millennia. As an assessment of human aspirations and motivation in the context of a "Space Ark," it would appear unlikely that many people would sign on for a journey beyond their lifetime. Call this effect the "Moses threshold." People may be willing to reach the mountaintop and see the promised land — or promised planet — even if they will be too old to live there, but a lifetime of totally deferred gratification would be an extremely hard sell outside of a few small monastic orders. This scenario might be the most that could be asked of humans as they are now constituted. A crew that knows they will die many generations before reaching their goal would seem to need an idealism so unrealistic or a desire to escape the earth so desperate that in neither case are they likely to make appropriate crew members. Never the less, many authors have delighted in the punchline of the space ark crew who were disappointed to find that someone departed after them to arrive sooner, using more advanced propulsion.

At the opposite extreme of the spectrum of interstellar travel possibilities, the relativistic round trip seems equally unrealistic as a millennial space ark. This unfeasiblity is not just because of the formidable propulsion problem, that no propulsion system now imaginable could produce the sustained delta vee necessary to achieve relativistic spaceflight. Robert Forward describes as "Stumbling Block 1" the idea that "A starship must accelerate continuously at one earth gravity." and goes on to argue that beyond a certain speed, the relativistic mass of the spacecraft increases to pose a trade–off of reduced travel time at the cost of greatly increased fuel mass.[4] However, if the difference between achieving, say, .75c and .99c means that the crew can arrive and return as heroes within their own lifetime, the additional expense may seem very worthwhile to them.[5]

This analysis of mission duration leads to the proposition that interstellar travel will be primarily one way and multigenerational, but with few enough generations that the original travellers or at least the descendents that they know will reach their destination. This criteria puts the focus on achieving at least the .05c range before interstellar travel becomes realistically feasible from the human factors and motivational point of view. This assessment reveals that a multigenerational journey to Proxima Centauri on the order of 80 to 100 years would be "pushing the edge of the envelope" to a great degree.

TRAVELLING SPACE COLONIES?

Perhaps the most widely cited catechism about interstellar spacecraft is that they would be essentially travelling space colonies[6] — constructed in space from millions of tons of materials, mined from the moon or asteroids, self–sufficient and multigenerational, with a population fixed at about 10,000 people. The underlying assumptions that drive the immense size are:

1) the need for a sufficiently diverse economy to provide the essential goods and services [7]
2) the need for sufficiently diverse vocational skills among the crew to support that economy [8], [9]
3) the need for sufficient cultural diversity to create a stimulating and dynamic society as "heterogenistic, mutualistic and symbiotic" [10]
4) the need for sufficient genetic diversity to guard against the emergence of undesirable recessive traits [11], [12] (e.g. hemophilia, Tay–Sachs, sickle cell anemia, etc).

The great practical difficulty in the O'Neillian space settlement schemes is the immense size and cost of these space settlements. The "Space Settlements" study of 1975 projected a construction cost of $190 billion in 1975 dollars, spread over 22 years (average of $8.6

billion/year)[13]. These estimates rely upon rosy predictions of mass to orbit costs. such as sending a space colonist into low earth orbit for $4,500 (in 1982 dollars).[14] With some baggage, bringing the average weight per passenger to 300 kg,[15] the cost per kg to orbit is a mere $15.00 (compared to about $2000 to $10,000 per kg, depending on how it is estimated, in the present Space Shuttle program). This cost is daunting given current or foreseeable technologies. Even at $15/kg to orbit launch costs, the annual space colony construction cost is more than the total NASA budget adjusted for inflation.

Beyond the obvious problems of raising and sustaining this size of budget, there are broader problems. Freeman Dyson estimated that the world GNP would need to grow by a factor of 1000 before it became viable to finance a space colony.[16] John Logsdon points out that for the foreseeable future, only governments, "alone or as lead partner, will be able to carry out major space activities such as space industrialization or space colonization." The unlikely or delayed return on investment is likely to deter private firms.[17] Ben Bova carries this argument further to point out that space colonies will impact upon the earth's economy, "Historically, when a colony becomes self–sufficient, it cuts itself free from its motherland. This helped bring about the collapse of both the British and Roman empires."[18] Thus, an earth or space colony–based society might not believe that an interstellar travelling space colony would be worth the cost.

Interstellar Spacecraft Size

To bring the interstellar spacecraft cost into the realm of possibility it would appear to be necessary to reduce the initial size and cost by at least an order of magnitude, which means reducing the crew size, or at least the initial crew size, by two orders of magnitude. This reduction in crew size means several fundamental changes in the common assumptions about a travelling space colony or "space ark." This smaller crew of 100 people would have a different set of tasks than the crew of 10,000, particularly as each crew member would need to learn multiple professions. However, they will have a lot of time on their hands to learn these skills during their century long journey.

HUMAN ACCOMMODATIONS

Perhaps one of the most vexing questions about interstellar travel is what would motivate somebody to go on a journey that he would very likely never complete, or if he did complete it, he might not have sufficient life left to him to benefit from the journey. Other than avid readers of science fiction or refugees from dire economic or political circumstances, it is difficult to imagine many people electing the lifetime of routine, monotony, boredom and constant peril associated with interstellar travel. Interstellar travel advocates love to cite the colonization of America and Australia as precedents. Despite the hardship of these voyages and the pioneering life that met the immigrants when they landed, the journey from Europe to North America was six to eight weeks, and to Australia, it was eight months to a year (and most of them were involuntary, convict immigrants). The problem of motivation is critical to any understanding of human factors issues on interstellar missions.

Maslow's Model of Motivation

The psychologist Abraham Maslow developed a model of human motivation as “an attempt to formulate a positive theory of [human] motivation.”[19] Although this model is not a scientific hypothesis about human behavior or human nature, it is a useful concept of human motivation and needs. It represents an attempt to create a synthesis of the diverse physiological, social, emotional, perceptual and cognitive bases of human motivation. The habitable environment is an influence on human motivation behavior, through gratification or deprivation, or a host of other perceptions or conditions.[20] Figure 3 illustrates Maslow's model as a hierarchical pyramid having five levels, characterized from the bottom up as: physiological needs, safety, belonging, self-esteem and self-actualization.[21] Each level is necessary to support the levels above it.

This diagram suggests the possibilities of interaction between different levels in Maslow's model. Health problems related to zero gravity or radiation could undermine crew productivity, reliability and capability for sustained performance, thus reducing the the effectiveness of teamwork, which in turn could compromise the monitoring and maintenance of thermal control and life support. These “cascading” system effects are characteristic of human error–caused disasters in aviation and nuclear power plants.[22]

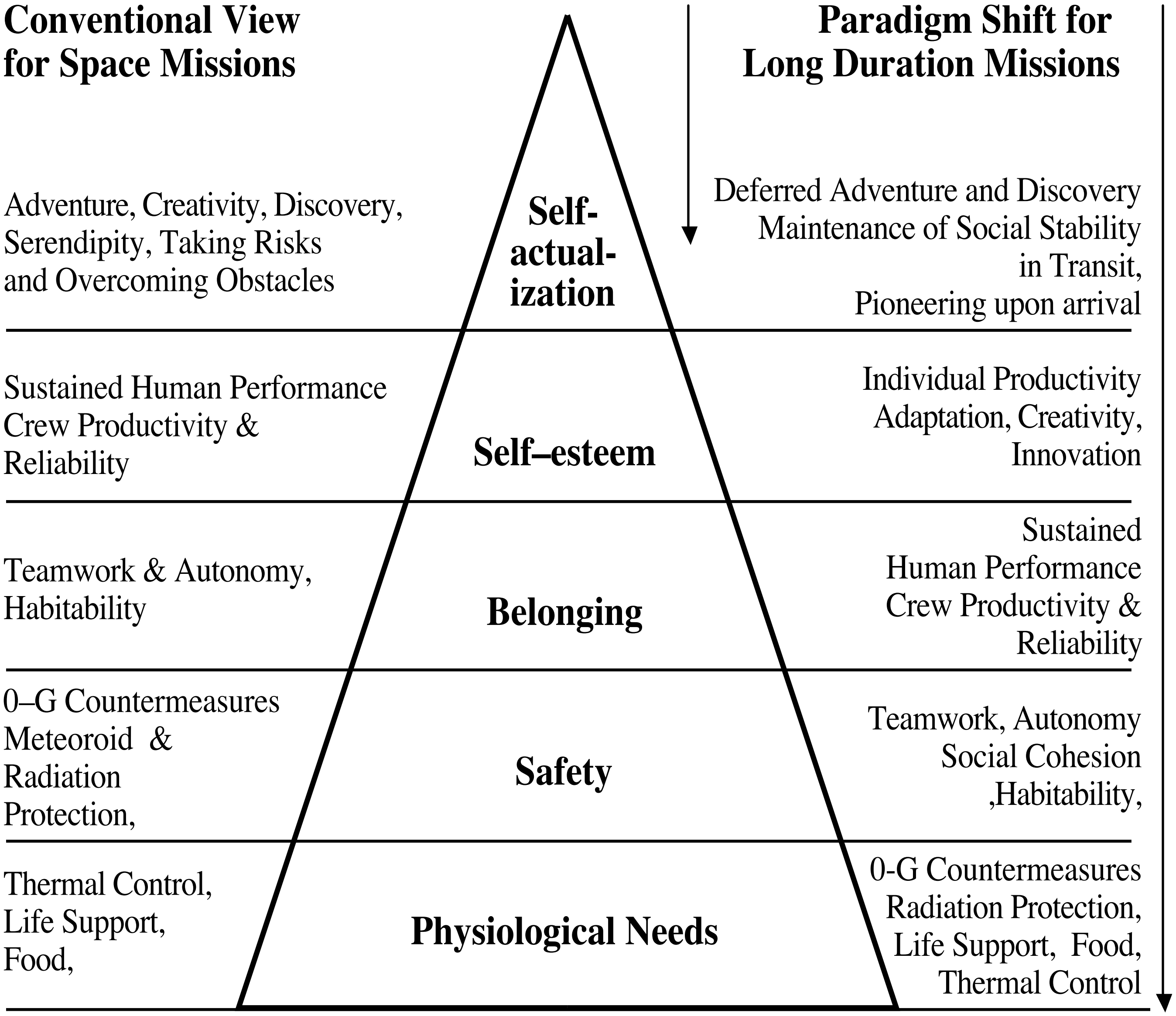
Maslow's theory has far-reaching implications for space habitat architecture. It matches up with issues in the current space station program and in the contemplated Lunar and Mars programs, shown to the left of the pyramid. While there appears to be fundamental agreement on physiological needs such as air, water, food and thermal comfort, as one moves up the pyramid, the issues become increasingly treated as expendable options. Connors, Harrison and Akins described the baseline human requirements for long duration missions.[23] However, Clearwater and Harrison argue that for Mars Missions, the engineering temptation to “trade–off” cost for comfort would be a “major mistake” from the human factors point of view.[24] If this precept is true for a Mars mission, it will be “true in spades” for an interstellar journey.

Human Motivation and Needs Paradigm Shift

The paradigm of space systems engineering holds that every component of a space program has features of cost and benefit that are subject to manipulation “trade–offs.” For a successful interstellar journey (and perhaps for most other, more near–term long duration missions) this paradigm must change to recognize that some elements are essential to crew performance beyond just keeping them alive and working long shifts. The alignment of mission system engineering values and decisionmaking will need to shift downward against the hierarchy of human motivations and needs in Maslow's model.

Countermeasures to weightlessness and radiation are good examples of how this paradigm shift will occur. Presently, both the Soviet and American space programs are contemplating missions to Mars (of 1 to 3 years) using drug and exercise countermeasures to counteract bone demineralization and muscle atrophy. They consider some degree of deterioration (and recovery after return to earth) as acceptable.[25] However, for a journey that lasts a lifetime, providing artificial gravity shifts from a safety trade–off option to an absolute physiological requirement. Similarly for radiation protection, the traditionally allowable exposure is measured by the month, 90 days or the year, but not for a lifetime. Raasch, Peercy and Rockoff state "The time is coming when the astronaut population will need to be considered as part of the general population and not a small and separate group with separate standards or radiation exposure levels."[26] Advocates of space colonies and interstellar space arks recognize both weightlessness and radiation exposure not as an optimizable safety trade–off but as an absolute physiological requirement.[27]

Other components of the space habitat would shift down the Maslow pyramid. Crew teamwork and autonomy will become more than a de facto residual of the supervisory role played by Mission Control in either Houston or Star City, and become instead an essential component of safety. The definition of human productivity will shift, from the focus on near–term economic return (although there has never been real economic return) to a view toward investment over the lifetime of the mission. This "new value" approach to productivity would place an emphasis on education, learning, skill–enhancement, quality, stimulation, feedback processes and adding value to the people and the organization.[28] The "new value" measure of productivity would approach work life as sustaining and enhancing the overall quality of life rather than the economic bottom line — the primary source of chronic stress. It suggests an "unpriced value" system of personal and professional development to encourage the creativity and serendipity required upon arrival at a new star or planet.[29]



Paradign Shift in Maslow’s Model of the Hierarchy of Human Needs, showing the effect of generational extended duration spaceflight.

HUMAN FACTORS TECHNOLOGY ISSUES

The emergence of human factors issues from the foregoing discussion takes on two thrusts: the philosophy / theory of human factors issues and the technology necessary to address those issues. The philosophical issues are largely imbedded in the approaches to the technology, and only become manifest in specific potential technical solutions. The key human factors technology issues in question are habitability, human–machine interfaces, crew selection, crew training, population control or growth and "transtellar sweat equity."

Habitability – the "Human–Environment Interface"

Habitability considerations will be crucial for interstellar travel; an essential component of operational safety, pushing the technology necessary for Mars exploration much further. Habitability issues will shift from support of human productivity to a critical factor in long term safety.[30] Life support, food supply and hygiene systems will need to be totally closed and self–regenerating. The way people live with these systems over the long haul will be vital to mission success. Both private spaces and group activity places will become much more important for crew social interaction and cohesion than presently conceived for Space Station Freedom. Public spaces for ceremonies, meetings and even courts of law would take on an importance comparable to terrestrial society. The internal architecture of the spacecraft would need be able to respond to changes and developments in the crew society. This flexibility would include the ability to metamorphosize the floors, ceilings, partitions and configurations of rooms and zones on the spacecraft.

One popularly cited alternative to investing in such an extensive infrastructure is to develop some form of hibernation or suspended animation technology perhaps through cryogenics or controlled stimulation of the mammalian "deep diving reflex." However, unlike most other technologies suggested for interstellar travel, the medical profession has not made any notable successes in "suspending" a subject and then reviving him.

The design of a vehicle to support an entire crew in suspended animation would involve profound safety provisions. What is fascinating about "The Big Sleep"[31] scenario is that it raises the ***external agency fallacy*** in much the same way as the solar–reflecting mirror or solar laser for solar sailing.[32] The entire destiny of the crew and the entire success of their mission would depend on a machine, an "ultra–reliable" computer to reawaken the crew members upon arrival at the destination. The crew would have have no control over the potential single–point failure source of a laser or mirror because they would be "asleep" or light–years away or both.

Human–Machine Interface

The domain of human–machine interfaces will grow in importance as the crew depends on automated "system executives." Crew and system autonomy will be not an option but an imperative as "mission control" recedes light years and generations behind them. When an emergency or "off–nominal" situation occurs, pervasive alert, caution and warning systems, and information displays and diagnostics will enable the crew to handle the problem by themselves, without consulting mission control.

The trend towards transparency of user interfaces for operating systems and training will extend into the domain of manufacturing on board the spacecraft. The design emphasis for onboard systems will shift from design for maintainability to design for manufacturability so that the crew can make new parts with a minimum of specialized knowledge. Highly automated “flexible manufacturing and assembly” systems will enable the crew to fabricate new parts to repair, replace or modify old ones, or to change or expand the spacecraft itself. It is essential to provide this manufacturing base so that the crew can begin to make the specialized tools they will need on the new planet's surface.

Crew Selection

Traditional crew selection techniques focus on a variety of aptitudes and vocational skills. For an interstellar mission, an added selection criteria will be the ability to teach those skills or professions and the social skills to succeed in the closed society in transit. Interstellar travel also introduces genetics as another new selection criteria.

Reducing the population reduces the gene pool as well. The technology that would allow a smaller gene pool would be genetic science along the lines of the nascent Human Genome Project. This knowledge would be part of crew selection, to reduce the possible emergence of unwanted recessive traits or other hereditary diseases to below a significant probability. J. B. Birdsell advocates meticulous crew genetic selection to diversify the gene pool as widely as possible to avoid undesirable recessive traits emerging. At the same time, he advocates simplifying certain gene selections, such as advocating that all crew members be Blood Type O, Rh positive, to make blood banks and transfusions much less complex than on earth.[33] These genetic approaches to crew selection raise profound issues of medical ethics, as well as a potential form of genetic fascism. The assumption that “homo space” would be some kind of genetic superman compared to homo sapiens deserves to be treated with great suspicion. The notion is particularly suspect that medicine or science can help human beings leave some undesirable part of their character or being behind while bringing with them only the attributes they consider most desirable. This kind of hubris can lead to tragedy.

A significant difference between this scheme and a space colony is to provide for population growth while en route to avoid the homeostatic quality of a rigidly controlled space colony. The travelling O'Neillian colony, with no growth or visitors, runs the risk of stagnating. No successful human society could long endure that way. However, the whole scenario becomes much more dynamic if the spacecraft is designed to accommodate four generations (great–grandparents and babies) of population growth. With the capability to maintain its equilibrium, the starship population will plan to grow. If the star travellers find it impossible to settle a planet at their destination, they could still choose to control population growth, and ideally, would have reached the point of balance with renewal. To allow for full generational realization (4 generations concurrently alive) the crew would plan for population growth from 100 to about 400 or 500.

Crew Training

Reducing the initial population of the interstellar vehicle from 10,000 to 100, reduces the potential skill base correspondingly. William Hodges, an economist, argues that an interstellar migration crew of 10 would be sufficient for “the cheapest possible spaceship.”[34] The interstellar crew would need new training and learning technologies that would allow for this reduction in the skill base. These new technologies would be cognitively and perceptually focused training techniques, incorporating “expert systems” and “virtual reality.” Some training tasks might be delegated entirely to computers or robots, but much of the training responsibility would necessarily devolve upon the crew members themselves.

It seems that there are two general classes of skills that will need to be maintained. Class one are the skills that the crew can practice and utilize while in transit, such as medicine, computer science, biology, chemistry, hydroponic/aeroponic agriculture and certain kinds of engineering, manufacturing or crafts such as mechanics or welding. Class two are those skills that the crew cannot practice until they reach the planet. These skills include farming, mining, drilling for petroleum, logging, civil engineering (dams, roads) hydrology, etc. — skills having to do with the exploitation and processing of natural resources. How would one teach farming to someone who has never stood on a planet or seen dirt? Expert systems and virtual reality could only take one so far at a conceptual level. At some point people must experiment with their own attempts at new solutions. Since the spacecraft is self–sufficient, the crew should have time to experiment at their destination.

Transtellar Sweat Equity

On a spaceship that can essentially fly and operate itself, what will the crew members do for their generations in transit? Certainly, they will train and train again to practice the skills they will need upon arrival at a new world. However, this vicarious practice will neither suffice to prepare the future pioneers for their destiny at a new star nor will it provide them with the satisfaction in their own work that comprises the apex of the Maslow Pyramid in Figure 3.

In order to hone the crew members' inventive and technical skills, to challenge them and to prepare them for pioneering, the crew would build and expand the interstellar ship in transit. This transtellar “sweat equity” would provide meaningful and useful activity to the new generations of crew members. The crew members would build all the components of new segments of the vessel from raw materials – including atmosphere – stored on board. The construction of new pressure shell modules would be one option, but they would also reconstruct or fill–in existing pressurized volumes. The crew would build new life support system components and develop new agricultural modules in anticipation of their future needs. Upon arrival at the new star or planet, the crew would be able to apply these robustly developed skills and self–sufficient spirit to their new home.

CONCLUSION

For interstellar travel to be realistically feasible from a human factors perspective, a starship would need to attain a speed of at least .05c, to arrive at Proxima Centauri in 80 to 100 years of multigenerational travel. To be financially viable, the initial crew size would not exceed 100 souls. However, the interstellar spacecraft would be designed to accommodate expansion or “filling–in” during interstellar transit, which would allow for natural population growth to 400 or 500. Among the critical human factors technologies for this interstellar mission will be habitability, crew selection and crew training. Crew training will involve a range of perceptual and cognitive aids to learning, including the heirs to “expert systems” and “virtual reality.” The long term success of the interstellar migration will depend on human motivation and the provision for human creativity, discovery, inventiveness and serendipity.

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[21] I am indebted to Profession James Wise for explaining Maslow's theory to me in this pyramidal form.

[22] Thanks to Mike Shafto, Asst. Chief of the AeroSpace Human Factors Research Division at NASA–Ames Research for these cogent observations on the implications of this interpretation of Maslow's model, and to Barbara Kanki of the Human Flight Factors Branch for her contributions to the diagram.

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