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Android Noahs and embryo Arks: ectogenesis in global catastrophe survival and space colonization

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Review Article

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Abstract

To ensure long-term survival of humans and Earth life generally, strategies need to be in place to recolonize Earth after global catastrophes and to colonize exoplanets. In one strategy of space colonization, the physical barriers erected by time and space are circumvented by sending cryopreserved human and animal embryos to exoplanets rather than adult crews. There the embryos would be developed to neonates in artificial uterus (AU) systems. A similar strategy could also be used to repopulate Earth after human extinction events. In this paper, we review the status and future prospects of these embryonic survival strategies. A critical requirement in each scenario is an AU system for complete ectogenesis, i.e. complete development of embryos to neonates outside the natural womb. While such systems do not yet exist, they may soon be developed to afford clinical assistance to infertile women and reproductive choices to prospective parents. In human survival schemes, AU systems would likely first be used to extend conventional survival missions (e.g. subterranean bunkers) by replacing some adult crew members with cryopreserved embryos. For major mass extinctions and all far future events, adult crews would be entirely replaced by embryos and androids. The most advanced missions would feature orbiting embryo spacecraft for Earth recolonization and analogous interstellar spacecraft for colonizing exoplanets. We conclude that an advanced civilization using such an integrated, embryonic approach could eventually colonize distant parts of its home galaxy and potentially the wider universe.

Introduction

In the last few decades, there has been increasing recognition that the future of our civilization on Earth could be bleak. Global warming is the immediate threat, together with its subthemes of sea-level rise, pestilence, famine and conflict. Yet there are many other ways our civilization could fail, from declining fertility rates to pandemics to replacement of humans by AI to simple urban decay (Baum, 2015; Avin *et al.*, 2018; Turchin and Denkenberger, 2018). While these threats individually might not be so severe as to cause human extinction, collectively they might conceivably do so (Kareiva and Carranza, 2018). Other events could on their own have a magnitude sufficiently high as to cause human extinction. Asteroid collisions could potentially destroy much or all of the biosphere and render the Earth uninhabitable for many years (Walkden and Parker, 2008). Other potential mass extinction events include solar processes (e.g. coronal mass ejections) and supervolcanoes (Denkenberger and Blair, 2018). The remaining classes of mass extinction events, chiefly of geological origin, have taken place frequently in the last 250 million years and are thus nearly certain to occur in the future as well. They include glaciation periods, including those of the ongoing Quaternary glaciation, and periods of episodic volcanism, which gave rise to at least four of the last five major mass extinctions (Wignall, 2005; Ward, 2007; Feulner, 2009). Finally, the steadily increasing luminosity of the sun will guarantee an end to life on Earth in a few billion years (Klee, 2017).

These multitudinous risk factors, especially the human-caused ones, have led to renewed proposals to safeguard civilization. The proposals include securing human populations in subterranean caverns; in giant ships orbiting the Earth; in lunar or Martian colonies; or, in the extreme case, on exoplanets. Subterranean bunkers remain a viable option for extinction events with low magnitudes and lasting not more than a few decades (Jebari, 2015), but not for a longer duration or higher magnitude events. Orbiting survival missions (e.g. *Asgardia*) have serious technical problems (Harby, 2018), while missions to terraform Mars lack theoretical viability (Jakosky and Edwards, 2018). At the extreme end, proposals for manned missions to exoplanets face such serious physical and biological constraints as to be entirely unrealistic (Klee, 2017).

There is, however, one lesser known strategy for colonizing other worlds which could not only potentially circumvent these constraints, but also serve as a template for survival missions

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here on Earth. This strategy is based on J.B.S. Haldane's prediction in 1924 that a baby would be born one day in an artificial uterus (AU), a process he termed 'ectogenesis' (Rosen, 2003). As shall be detailed herein, major advances since Haldane's time have been made towards developing an AU (also termed 'artificial womb' or 'artificial placenta'). Recognizing the severe limits of manned space travel to exoplanets, science fiction authors have long speculated that human babies developed from frozen embryos in artificial uteri would be the first colonizers of distant worlds (Crowl *et al*., 2012; Hein and Baxter, 2019). The strategy has recently received more serious attention, however, and has been termed Embryo Space Colonization (ESC) (Crowl *et al*., 2012; Hein *et al*., 2012). The spacecraft in ESC have been referred to as 'seedships' or sometimes as 'founder probes' (Hein and Baxter, 2019). In the context of interstellar travel, replacing adult humans with cryopreserved embryos or gametes would solve many problems at once. Since the requirements for fuel, food and spacecraft maintenance would be reduced to the minimum degree possible, the interstellar journeys could proceed leisurely, with existing propulsion methods, and thus take thousands or even millions of years. The level of technological expertise needed to design and launch embryo ships would nonetheless be daunting. At a minimum, these missions would need to (a) navigate space for millennia using only machine intelligence and then land on exoplanets; (b) develop cryopreserved embryos in robotic AU systems; and (c) raise humans, animals and plants in ecosystems constructed *de novo* using robotic assistants and AI.

A point not generally recognized, however, is that many of the techniques of ESC could also be used in recolonizing Earth after human extinction events. Moreover, given the immediate urgency of planning for these extinction events, it is here rather than on exoplanets that these techniques would likely first appear. To underscore the analogy with ESC, we will term this latter type of mission Embryo Earth Recolonization (EER). Compared to ESC, the approach of using post-apocalypse Earths rather than exoplanets as the primary colonization targets would simplify mission designs dramatically. In most cases, there would be no need, for example, to sequentially introduce a full suite of microbial, plant and animal species to make Earth habitable for humans again. In addition, much of the equipment, chemical supplies and infrastructure (e.g. androids, shelters) of EER missions could be stationed in subterranean structures here on Earth. The problem for EER missions would essentially reduce to designing AU systems and AI systems able to raise humans and animals from cryopreserved embryos.

In this paper, we will review ectogenesis with cryopreserved embryos as a strategy to recolonize post-apocalypse worlds and to colonize exoplanets. We will first examine artificial womb technology and embryo cryopreservation in relation to their possible use in ESC and EER. Subsequently, we will consider how these technologies might actually be deployed in EER and ESC missions.

Ectogenesis and embryo cryopreservation

The core issues in both EER and ESC concern the design of AU systems able to develop cryopreserved embryos and the long-term viability of those embryos. Designs for AU systems are currently advancing at a rapid pace, but with the alternative goals of assisting extremely premature infants survive a critical stage of development and safely reach the neonate stage and, for some parents, to allow reproduction totally outside the natural womb. The AU systems being designed for premature infants only attempt to realize partial ectogenesis, i.e. facilitating just one stage of foetal development outside the natural womb. Such systems require surgical attachment of the veins and arteries of the premature infant to the AU. As such they are not strictly applicable to EER and ESC missions, where the cryopreserved embryos must be able to make the connection to the AU without any surgical intervention. The AU systems for these missions must thus support complete ectogenesis, i.e. complete foetal development to birth entirely outside the natural womb. As AU technology for partial ectogenesis would also be needed in systems for complete ectogenesis, it will be considered first.

AU systems for partial ectogenesis

With the increasing recognition of the extremely premature infant as a potentially viable neonate, there has been an upsurge of research on AU systems in the last few decades (for reviews, see Bulletti *et al*., 2011; Bird, 2017; Partridge *et al*., 2018). Various names have been given to these systems, including artificial uterus, artificial placenta and artificial womb. They are primarily aimed at the group of premature infants born in a so-called 'grey-zone' of 23–25 weeks, when lung development is at a critical stage. In essence, the AUs attempt to put off the transition to neonatal life, marked by the infant's first breathing, by extending the period of foetal development.

To achieve this, these systems must perform all the key functions of the natural placenta. Oxygen and other substances pass through a semipermeable membrane between the foetal and maternal blood supplies, which do not mix. In addition to oxygenation, the natural placenta maintains the foetal circulatory configuration and haemoglobin levels; supplies nutrients; mediates the foetal heart rate and blood pressure; maintains fluid balance and electrolyte composition; and acts as kidneys in eliminating nitrogenous waste substances from the foetus. AU systems must attempt to match the natural placenta in all of these and other tasks as well.

Major breakthroughs have been made in AU systems in the last few years. The new systems have been tested mainly on preterm foetal lambs. A core process in AUs is extracorporeal membrane oxygenation (ECMO), the transfer of air or oxygen directly into blood across a gas-permeable membrane. In one commonly used system, the EMCO unit is connected to the foetal circulation via two umbilical arteries and the umbilical vein. Using this method, a 'biobag' designed by Partridge *et al*. (2017) was able to support foetal lambs for periods up to 4 weeks. An AU system called *ex vivo* uterine environment therapy was similarly able to keep premature lambs alive and healthy enough to survive to infancy (Usuda *et al*., 2019). In these systems, the foetus is secured inside a plastic bag and surrounded by artificial amniotic fluid, which is routinely filtered out and replaced. The pace of advancement in this field has been so rapid that systems of partial ectogenesis for extremely premature infants are expected to be ready for clinical use in just a few years.

AU systems for complete ectogenesis

As noted above, AU systems for partial ectogenesis go only part of the way to the type of system needed for EER and ESC missions. The latter require AU systems for complete ectogenesis, the implantation of embryos and full development of foetuses

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outside the natural womb (for reviews, see Bulletti *et al.*, 2011; Healey, 2016; Simopoulou *et al.*, 2019). While this eliminates the intricate surgical interventions required to make the foetal-AU connection in partial ectogenesis, it requires successful implantation of the embryo in a surface mimicking the natural uterine wall.

The most direct way to achieve this implantation would feature a whole or partial natural uterus attached to an *in vitro* AU of the partial ectogenesis type. The resilience of the natural uterus was recently demonstrated with live births of human babies after uterus transplantation to infertile women (Brännström *et al.*, 2015; Brännström, 2017; Suganuma *et al.*, 2017; Kisu *et al.*, 2019). It is noteworthy, however, that a complete uterus might not be needed in EER and ESC. The uterine functions of contractility and amniotic sac enclosure, for example, would not be required if embryonic development transpired within an artificial amniotic sac of the 'biobag' type. Successful implantation of human embryos *ex vivo* had earlier been achieved in human uteri maintained through extracorporeal perfusion (Bulletti *et al.*, 1988, 2011). The embryos were able to grow for several days before the experiments had to be terminated for legal reasons. For EER and ESC, natural uteri would also need to remain functional after prolonged cryopreservation. In this regard, Dittrich *et al.* found that cryopreserved swine and sheep uteri perfused with a cryoprotectant remained viable for many hours post-thaw, as shown by their ability to produce rhythmic contractions after oxytocin administration (Dittrich *et al.*, 2006, 2010*a*, 2010*b*; Schölch *et al.*, 2012). These studies together are suggestive that cryopreserved natural uteri or uterine tissues attached to an *in vitro* AU system might eventually form the basis for EER and ESC missions.

An alternative route to complete ectogenesis was devised by Liu *et al.* at Cornell University (Liu *et al.*, 2001; Reynolds, 2005; Bulletti *et al.*, 2011; Healey, 2016; Simopoulou *et al.*, 2019). Liu *et al.* stretched sheets of endometrial and stromal cells over a biodegradable scaffold and then shaped the tissue into the form of a natural uterus. While the results were never published, it was reported that human embryos in their study were able to successfully implant in this tissue and grow for up to 10 days before legal restrictions once again halted the experiments (Reynolds, 2005; Bulletti *et al.*, 2011). Subsequently, Liu *et al.* were able to implant mouse embryos in a murine model uterus made in this way and grow them almost to full term, at which point however all either died or were found to have deformities (Reynolds, 2005; Healey, 2016). In a follow-up study, murine embryos grown on engineered uterine tissues and then transferred to the abdominal cavity of adult mice at 7 days were found to be anatomically normal and apparently healthy when removed close to term (Healey, 2016). In spite of such findings, Liu *et al.*'s experiments in this area tapered off, possibly due to the bioethical controversy that they stirred up (Reynolds, 2005).

Still another method of complete ectogenesis involves interspecies pregnancies (or 'xenopregnancies'), in which the species of an embryo or foetus and its uterine carrier are different (Wang *et al.*, 2001; Bulletti *et al.*, 2011). In this technique, embryos of mammalian species are implanted in the uteri of closely related species. Species similarity is necessary to minimize immune rejection and problems arising from species differences in placental and uterine systems (e.g. inappropriate interactions between the foetal trophoblast and the endometrium of the mother). In EER and ESC, the first species of mammals to be introduced, which would require some different type of AU system, could then serve as the embryo carriers for slightly larger mammals. Progressively larger mammal species could then be introduced, with humans appearing near the end of the sequence. This method of ectogenesis would be a vast research undertaking, however, requiring major advances in immunology and other fields. It would also raise ethical objections if ever it came to fruition (Bulletti *et al.*, 2011).

From the foregoing, it can be seen that more research is needed before the true potential of ectogenesis for EER and ESC missions can be known. While xenopregnancies could eventually prove superior for these missions, due to their natural robustness, the most realistic designs in the near term would likely feature the natural uterus or a portion of it attached to an *in vitro* AU system. The natural uterus or its component would conceivably be connected to the *in vitro* AU and cryopreserved *in situ* until the time it was required. Or, adapting the uterus modelling techniques of Liu *et al.*, artificial uteri for each species might be made by layering endometrial and stromal cells onto an *in vitro* AU and holding the whole unit in cryostorage for the mission duration. Alternatively, *in vitro* AUs could be modified on site robotically at the appropriate time by incorporating uterine cells from cryopreserved cultures.

A potential problem for ESC, as noted by Hein and Baxter (2019), is that the human embryo alone is insufficient to make a human. A vast population of bacterial species are also needed to form the complex microbiomes which inhabit the intestinal tract and other parts of the human body. To address this situation, it would be necessary to cryopreserve bacterial cultures representing the various components of the microbiome, which would later be thawed out and administered robotically.

While the bioethical and legal issues surrounding partial ectogenesis are already numerous and complex, they become markedly more so for complete ectogenesis (Schultz, 2010; Hammond-Browning, 2018). The debates on these issues are significant in the present context, as the research underpinning AUs for complete ectogenesis will likely not be inspired by EER nor ESC, but rather by the reproductive needs and choices of ordinary people. As discussed by Healey (2016), there are many potential clinical advantages of complete ectogenesis. It could significantly reduce the morbidity and mortality for the 15% of pregnancies with potentially life-threatening complications and also eliminate *in utero* infections and exposures to teratogens (e.g. fetal alcohol syndrome, cytomegalovirus). Complete ectogenesis would allow women with injured or diseased uteri to conceive and carry infants to term *ex vivo*. It could also prove more efficient and provide better outcomes in some cases than ordinary IVF procedures. MacKay (2020) noted that complete ectogenesis could liberate women from societal pressures in reproduction generally and thus reduce certain negative practices, such as surrogate motherhood and uterine transplantation. On the flip side, complete ectogenesis could accelerate a trend towards making women's life trajectories more similar to men's and thus pressure women even more to compete with men on men's terms (Buturovic, 2020). The most difficult and perplexing bioethical and legal issues, however, concern the status of embryos themselves (Schultz, 2010; Hammond-Browning, 2018). It is these issues which have likely impeded research on complete ectogenesis relative to partial ectogenesis. Their resolution would seemingly be necessary before serious progress on AUs for complete ectogenesis can be made. Only if and when such systems come to fruition could they be evaluated for possible use in ESC and EER missions.

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Viability of cryopreserved cells and embryos

Another critical issue for EER and ESC concerns the long-term viability of cryopreserved cells, seeds and embryos. The potential periods of cryostorage involved range from just a few decades in short duration EER projects to millions or even billions of years in longer duration EER and ESC missions. Our knowledge on this point stems mostly from the practice of IVF following embryo cryopreservation (for a review, see Bosch *et al.*, 2020). Cryopreservation of embryos in IVF is achieved either using a slow freezing method or a fast freezing method termed vitrification (Rezazadeh Valojerdi *et al.*, 2009). In one study, no correlation was found between the storage time of frozen embryos and their post-thaw survival and pregnancy outcomes (Riggs *et al.*, 2010). Implantation, clinical pregnancy, miscarriage, and live birth rates were similar for patient groups regardless of the duration of storage. In addition, increased rates of point mutations have not been found in cryopreserved embryos over a range of storage times (Caperton *et al.*, 2007). Significantly, babies have already been born from embryos that had been cryopreserved for up to 24 years (Zhang, 2017). In the context of EER, this is already a period which could span many kinds of short-duration extinction events.

There is also evidence that embryos can potentially be cryopreserved for much longer periods. With the low levels of background radiation experienced on Earth (0.1 rad year^{-1}), it has been estimated that human embryos could be stable for thousands of years (Quintans *et al.*, 2002). Cryopreserved embryos could also remain viable for many years under the conditions of space, where key segments of some EER and all ESC missions would unfold. Wakayama *et al.* (2017) found that space radiation of mouse spermatozoa stored for 9 months at −95°C on the ISS, where radiation levels due to sunspot cycles and cosmic rays are 100 times higher than on Earth, did not lead to a subsequent loss in fertility or birth rates or an increase in birth defects.

Even with supreme advances in the design of refrigeration and power generation systems, however, it cannot be expected that embryos could be cryopreserved on a post-apocalypse Earth for more than a few decades. Consequently, there would be an imperative in longer term EER missions to cryopreserve seeds and embryos in orbiting spacecraft. In orbits around Earth, the Moon or, if necessary, Mars, the coldness of space would serve as a natural refrigerator, allowing seeds and embryos to be cryopreserved indefinitely with minimal mechanization. Around Mars, in particular, solar radiation would also be too feeble to heat any part of a spacecraft appreciably or induce harmful effects on DNA. The orbiting EER ships would remain there until conditions on Earth were determined to be favourable for return.

In certain EER missions and all ESC missions, a vast number of microbial, protist, plant and animal species would need to be introduced to reconstruct working ecosystems. It would be highly impractical to grow all the species of an ecosystem individually. Instead, samples of soil and sea/river bottom would likely be cryopreserved in entirety – not unlike the soils of a northern marsh in winter – and thawed out together. The samples would contain the key microbes, plant seeds and fungal spores of the ecosystem, along with the eggs and larvae of invertebrates and small vertebrates.

We lastly note recent evidence suggesting that microbial species can remain viable over millions of years *without* cryopreservation. Bacteria from many groups that had been retrieved from deep sea sediments were successfully revived after existing in a dormant state for 101.5 million years (Morono *et al.*, 2020). Almost all of the microbes in the samples survived despite having essentially no nutrients for all that time. This remarkable finding hints at the possibility of alternative systems for long-term storage of cells and embryos without cryopreservation, ones conceivably using nutrient-free gels, for example. Discovery of such techniques would vastly extend the range and duration of both EER and ESC missions, as the need for bulky refrigeration equipment and the energy to drive it would be mostly eliminated.

Embryo Earth Recolonization

Assuming that AU systems for complete ectogenesis will eventually become available, we next consider how they might actually be deployed in EER and ESC missions. As discussed above, artificial and natural mass extinctions together with passive agents of civilization decline will divide the future Earth into intervals when advanced societies are present and ones where they are not, with a final black zone with no life at all. Considering the multitude of possible agents of mass extinction, an advanced civilization might conceivably attempt to design survival plans to address each type of extinction event specifically. A far simpler and more realistic approach, however, would involve a civilization preparing for any and all manner of extinction events, whatever their magnitude, suddenness or duration. Such an integrated and comprehensive approach could achieve many efficiencies not found in piecemeal plans. The groundwork for such plans could be laid in conventional survival missions, in which adult human colonists are secured in subterranean bunkers, orbiting spacecraft or a combination of these two. These conventional missions could then easily be extended using embryo techniques to cope with events of progressively higher magnitude.

An integrated scheme incorporating both subterranean and orbital components is shown in Fig. 1. Each mission component will be referred to in the text below by its corresponding number in the figure. The integrated approach is best illustrated by working through survival scenarios in the order of increasing event magnitude and duration. The first extinction events to be considered are thus short duration events lasting not more than a few decades. These would include the ongoing episode of global warming and other events with human causes or affecting humans exclusively (e.g. bioweapons, nanoweapons, pandemics). Survival plans for these events would likely feature underground bunkers of the kind already in existence or conceptualized [1]. To be effective against multitudinous extinction events having a stochastic and unforeseeable quality – so-called *black swan extinction events* – these installations would need to be stationed at remote sites across the globe and be manned continuously (Jebari, 2015). At the same time, they would need to be optimally positioned to have favourable agricultural conditions during subsequent recolonization. Suitable locales might be found, for example, in river valleys or the rice terrace regions of China or the Philippines. The installations would need to hold at least some dozens of colonists; be self-sufficient in food stores and energy for a few decades; and have sufficient plant seeds and domesticated animals on hand to allow for the creation of a farming lifestyle once suitable environmental conditions returned.

The other conventional approach available for short duration events, as noted above, would feature spacecraft orbiting the Earth and carrying a small adult crew. As with the subterranean schemes, there would not be an embryonic component to such missions at first. These ships would simply remain in orbit

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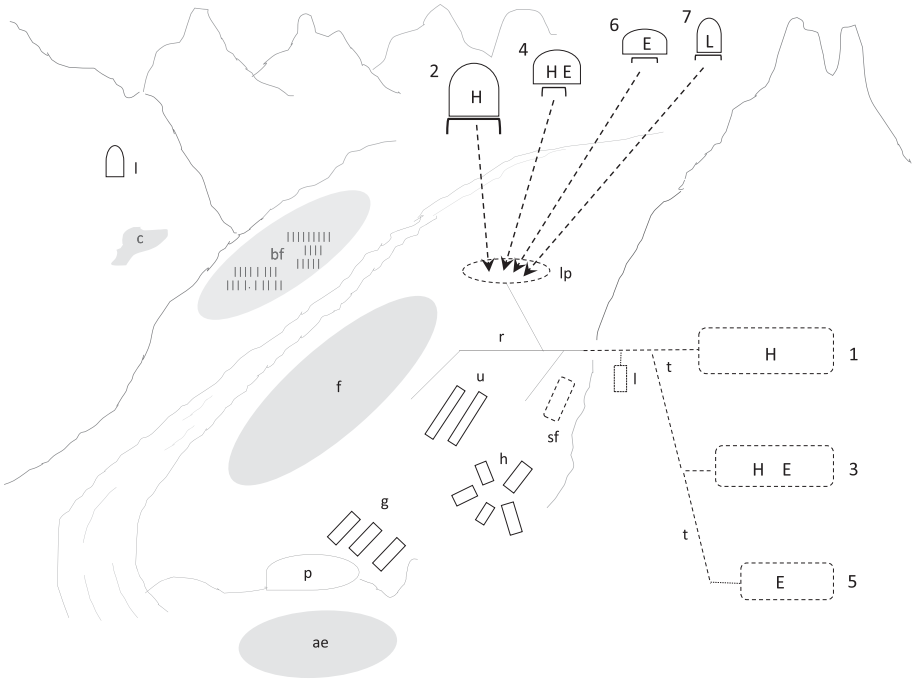


Fig. 1. Integrated scheme for mass extinction survival incorporating subterranean and space elements. Large dotted rectangles represent subterranean missions for different situations, set under a mountain at three depths. The four landers represent different orbital missions proceeding at different times. Colonists: H – adult human; E – human/animal embryos. Mission elements: 1 – crew subterranean; 2 – crew orbital/subterranean; 3 – crew/embryo subterranean; 4 – crew/embryo orbital/subterranean; 5 – embryo subterranean; 6 – embryo orbital/subterranean; 7 – library. Site features: t, tunnel; r, road; sf, solar farm; h, housing structures; u, utility sheds; g, greenhouses; p, fish pond; ae, telemetric animal enclosure; lp, landing pad; f, crop fields; bf, bamboo forest; l, prebuilt library; c, natural cave. See text for full descriptions.

about Earth, the Moon or Mars for years, waiting for just the right environmental conditions to reappear. From a logistical standpoint, it would make little sense for such advanced craft to land at unprepared sites, as the pressures of immediately establishing shelters, energy sources and growing crops would be enormous. An orbiting mission would thus likely be paired with a ground installation to form a combination mission [2]. This type of mission would again only be sustainable for extinction events lasting up to a few decades. For longer events, the orbiters would soon take on the character of so-called 'world ships' or 'generation ships' (see Hein *et al.*, 2012, 2020) and ultimately succumb due to mechanical breakdown or social disruption.

The next class of mass extinction events to consider are those of medium duration, lasting anywhere from a few decades to a century or so. An event of this class might be caused by an extremely large meteor or comet strike. For such events, the need to sustain an adult crew over many decades or a century would become technically overwhelming and an alternative approach would be needed, one in which at least some of the colonists are initially in embryo or gamete form. From existing IVF records, mentioned above, it is known that embryos and/or gametes could be preserved cryogenically at subterranean sites for many decades at least. For each adult colonist replaced by an embryo counterpart, the required amounts of food, water, housing and energy would be reduced accordingly. These hybrid missions [3] could thus be housed in much smaller facilities situated below the chambers of non-embryo missions [1], where greater protection would be afforded during a cataclysmic event. A hybrid project of this type would be overseen by a small number of colonists, who would maintain the refrigeration, water and power-generating equipment and, if possible, a core population of small farm animals. Genetic diversity in humans and animals would be enhanced in the early stages through artificial insemination or embryo implantation in females. In this way, large and diverse populations could be gradually raised from a very small number of females and artificial uteri.

As was the case for the subterranean missions, cryopreservation could also be used to extend the duration of orbiting missions. The orbiters in that case would now carry a small crew of a dozen or so and a great many embryos. An orbiter [4] once again would most logically be paired with a subterranean installation [3], using the latter's foods, fuel and equipment.

Missions for major mass extinctions and far future events

Up until this point, the extinction events which we have considered are ones which might occur in the relatively near future, less than a century from now, and which have a duration not longer than a century. We next examine those extinction events which might occur in the far future and/or have much longer durations. First on this list would be fast onset events caused by extremely large asteroid strikes, possibly larger than any heretofore experienced on Earth, or by powerful solar or geophysical events (e.g. supervolcanoes). Such events could have such a devastating impact and long duration that subterranean or orbital schemes with any adult colonists at all would no longer be feasible. Instead, all missions would need to become totally automated EER missions. Of these, there would be again two varieties, one which simply adapts the subterranean schemes discussed above and one which likewise adapts the orbiting spacecraft schemes.

For the subterranean project, the approach would employ bunkers at the same installations as described above, but set still deeper underground [5]. Packed with refrigeration and power-generating units and manned solely by android technicians, these deep bunkers could keep the embryos and seeds viable for many decades at least. The limiting factor here, as already noted, is the lengths of time that the refrigeration units, power supplies and androids could stably cryopreserve the seeds and embryos. With sufficient equipment and supplies, this approach could conceivably extend missions up to or just beyond the century mark. At the time when surface conditions renormalize, trailers holding the seeds, embryos, androids and equipment

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would make the ascent through tunnels to the surface. The surface phases of the project would be similar to those of the analogous orbiting mission discussed below.

For extinction events of still greater duration, however, it would no longer be feasible to cryopreserve seeds and embryos in subterranean installations. After periods of a century or so, all the refrigeration and power units would have failed. In addition, certain collision events could have such a high magnitude that Earth's surface partially melts. To address these situations, it would become necessary to move all seeds and embryos to spacecraft orbiting Earth, the Moon or Mars. These embryo ships would need to retain their functionality minimally for many decades or centuries, but ideally for thousands or millions of years. Many or most EER ships would be designated to become active at far future epochs subsequent to mass extinction events that had transpired then. Since their electrical and electronic components could not operate continuously for such extended periods, these ships would need to adopt a seed-like aspect themselves. In this respect, they would resemble the spacecraft of ESC missions.

An embryo ship of this type would periodically scan the Earth surface to determine the prevailing environmental conditions on each continent. In the interval subsequent to the mass extinction event, it is conceivable that human survivors of the cataclysm had regrouped to establish an advanced society, likely drawing upon cultural relics of our own. Alternatively, an intelligent animal species could have come to form a new kind of society altogether. In these cases, the EER mission would be able to demonstrate a marked flexibility in response relative to manned missions. It could choose to assist the new society to develop more rapidly if the situation warranted. Alternatively, it could opt to avoid contact altogether and wait on standby for a more appropriate time. Supposing that intelligent life is not found, however, the path would be clear to initiate the colonization sequence. In parallel with the other scenarios discussed earlier, two broad types of mission can once again be envisaged. In one type of mission, colony sites would have prebuilt infrastructure already in place, again using installations of earlier missions. In the other type, no preselection or preparation would have been done and the colonies would simply develop *ab initio* at the target sites.

We consider first the far more effective type of mission using prebuilt ground installations, with the assumption being made that the Earth's surface has remained largely intact [6]. At a chosen installation, one or more small modular craft would detach from the mother ship and be deployed to the surface. These modules would then begin the task of growing the desired microbial, plant and invertebrate forms in light, greenhouse-like structures. Any components that had been housed at the installation and were still functional (e.g., robotic assistants, chemicals, generators, shelters, greenhouses, etc.) would be moved out at appropriate times to be used by the landing modules. The installation's caverns might be able in some situations to afford a protective home. Crops suitable for humans and animal species would first be cultivated around the site by light-weight robotic gardeners and drones. Once sufficient yields had been obtained, the next wave of small modules would be deployed from orbit, carrying the embryos of key animal species (e.g. chickens, goats, fishes). Mammalian embryos would be incubated in artificial uteri, similarly as for human colonists, the artificial blood supply derived from already farmed plants and animals. Larger domesticated animals would be introduced only at a later stage, their movements controlled with telemetry. Fish farms could be made in nearby streams or lakes or in excavations for fish ponds near these waters. The equipment and supplies on the prebuilt installation – including tools, ploughs, tractors, explosives, etc. – would drastically increase the degree of landscaping and cultivation possible.

All of these steps for developing a pioneer farm would notably be attained without human farmers. Rather, a farm-like setting would be created robotically *de novo* and human babies then introduced into it. At the appropriate time, one or more larger modules holding cryopreserved human embryos would detach from the orbiting ship and land at the colony site. Upon reaching full term in artificial uteri, the babies would be raised in nurseries by android guardians. The androids' jobs would be made easier with an array of electronic devices already in the early stages of development. iPad-like devices equipped with eye-gaze technology, for example, could assist infants in quickly learning to read. The ability of androids to act as nurses is likewise easy to imagine, given that the biological functions of infants would be electronically monitored at all times.

With respect to ESC, Hein and Baxter (2019) noted that the psychological stress induced by departures from normal child-rearing practices could be severe. It should be noted, however, that the conditions facing child colonists in EER and ESC could be far better than those encountered by colonists in other types of survival or space missions. Food sources would have already been secured for them and the farm-like setting would engender some degree of emotional security. In addition to the parent-like androids, each colonist would be raised with a cohort of sibling-like members. Together with older and younger cohorts, the sense of a growing family and tribe could be instilled in children.

The second general scenario for resettling Earth would apply to very high magnitude extinction events, in which prebuilt EER installations either did not exist or else had become unusable (not shown in Fig. 1). Totally self-contained, these orbital missions would be the most challenging type of EER mission and in many ways would resemble ESC missions to exoplanets. In this case, there would be an even greater focus on finding locations ideal for farming and affording some measure of protection, such as natural caves. The orbiters and landing modules would need to supply all equipment, foods and supplies for the missions, which would accordingly be highly stripped down compared to the installation-based approach.

Libraries and library missions

A key requirement of any EER mission would be good functioning libraries containing the stored records of human knowledge and history. It should be noted that the computer files of the landing modules and androids would have only a limited lifespan once they were back on Earth, owing to their now steady use and exposure to Earth's surface environment. Consequently, small libraries would also need to be prebuilt inside the underground installations and also outside (Fig. 1). The books contained therein would need to be non-digital and have supreme durability, permitting use for centuries or longer. Even many years after the initial colonization, people coming upon such libraries might then still access Earth's archives and so, like the monks in *A Canticle for Leibowitz*, climb the ladder of knowledge.

The chances of an advanced civilization emerging on future Earths could be increased yet further if a global strategy for restorative libraries were employed. To this end, both digital and physical libraries might be housed in hundreds of small spacecraft continuously orbiting the planet [7]. These spacecraft,

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upon detecting a society or an EER colony possibly in need of critical information for advancement, would land nearby or deploy a landing module there. Within the philosophical framework of EER, a future Earth lacking a technological civilization is fundamentally a dangerous one so far as the long-term survival of Earth life is concerned. Pre- or post-technological societies would not only be incapable of launching EER projects when most critically needed, but would also fail to send ESC missions to exoplanets, thereby sentencing all Earth life to final extinction. These informational crafts or modules could potentially be deployed from orbit at any future time on Earth prior to the final extinction.

Impact on the Drake equation

Though the intelligent species of advanced civilizations on exoplanets could have markedly different biologies than our own, it can reasonably be inferred that the adult would typically develop from an embryonic stage. In this case, the same general logic outlined above for humans would apply for advanced civilizations elsewhere. While some might opt for a passive approach in the face of oncoming extinction, a majority would likely assert that the condition of continuing existence would always be preferable to cessation thereof. Many advanced civilizations might thus potentially adopt the EER and ESC approaches to project themselves and their ecosystems forward in time and outward in space.

In this case, EER and ESC could potentially alter the estimates of N in the Drake equation. This would chiefly be through the term L, the average lifetime of advanced civilizations, which is considered the most difficult term in the equation to firmly estimate (Drake, 2013). Through the techniques of EER and ESC, it would be possible for advanced civilizations to extend themselves into the far future. Let us combine the average lifetimes of advanced civilization and of their successful daughter civilizations engineered through EER and ESC in all future epochs in the single term, L. If each of the daughter civilizations were typically short-lived, L could still be as low as a few thousand years. But if the daughter societies were generally long-lived and effectively colonized all the later intervals of habitability on a planet, it could be as high as a billion years. Further progress in estimating the individual lifetimes of all the daughter civilizations would be needed before its total effect on the Drake equation and N can better be known.

Embryo Space Colonization

The techniques of recolonizing post-apocalypse Earths via EER maximize the total time during which advanced human civilizations might potentially exist on Earth. The Earth itself has but a finite lifetime, however, and so the critical question remains of how its advanced civilizations could branch out into space. Given that the other planets in our Solar System are forbidding abodes for Earth life and that terraforming techniques are unlikely to change this significantly (Jakosky and Edwards, 2018), our civilization would need to recreate itself on exoplanets. While it has been debated whether space colonization is even a correct ethical stance (e.g. Billings, 2019; Green, 2019; Smith *et al.*, 2019), we again make the general assumption that advanced civilizations, here and elsewhere, would want to continue their existence in deep space and deep time. The distances and times to transport astronauts together with their food and support systems to distant stars, whether in conscious or in hibernating states, are far beyond what is possible with known propulsion methods (Hein *et al.*, 2012, 2020; Klee, 2017). None exist which can accelerate ships to the speeds required. For example, the current speed of the Pioneer 10 spacecraft on its way out of the Solar System is only about 12 km s^{-1}, or 0.000041 c. At this speed, it would take 100 000 years to reach the nearest star, far too long for continuous maintenance of spaceships and sustenance of adult crews. We are therefore forced to revisit ESC.

Of the several possible missions discussed above for EER, the only one relevant for ESC is the final one, in which orbiting ships holding cryopreserved seeds and embryos are deployed at colony sites lacking prebuilt infrastructure. Once an embryo ship targets a suitable star and goes into orbit around an Earth-like exoplanet, the steps to human colonization would be very similar to that EER mission. Greater flexibility would of course be needed in the mission design to allow for the many ways in which the planet's weather, water and soils could differ from Earth's. The major difference with the EER missions is that the components of an entire, functioning ecosystem of Earth – including bacteria, protists, insects, mammals and birds – would also need be brought along. As was noted above for EER, bacteria, protists and small invertebrates (e.g. insects, worms) would be transported as frozen samples of soil and water representing various ecosystems of Earth. These would be carried down from the seedship by modular craft and planted at suitable times and locations. After each such modular descent, the mother ship would remain in orbit, possibly for decades, awaiting suitable changes on the surface to prompt the next modular descent. As in the analogous EER mission [6], humans would be one of the last species to be introduced.

The other main difference between embryo colonization of future Earths versus exoplanets lies in the extra adaptations needed for interstellar space travel. In ESC, the spacecraft must first gain sufficient velocity to escape the Solar System, travel to the target star and then decelerate to enter orbit around a suitable planet. Both the acceleration and deceleration stages require far greater fuel quantities than EER orbiters. There would thus be a need for substantial miniaturization of all the spacecraft components and a scaling down of the number of transported species and human embryo colonists compared to EER missions. The mission payload would therefore be much smaller too, possibly no more than a thousand kilograms. This would mostly be taken up by refrigeration equipment, solar power assemblies, some starter foods and androids. Hein and Baxter (2019) imposed an additional burden on a seedship of being a 'founder probe' – i.e. one capable of self-reproduction and extensive manufacturing in order to create habitable environments for later arriving expeditions. Here, however, we consider the migratory task to be entirely retained by the individual seedships, with no requirement of follow-up missions. As these seedships would be much smaller than founder probes, the transit times required to reach their destination exoplanets would be significantly reduced. These times could be reduced up to 100 times faster still by carrying out slingshot manoeuvres around other stars encountered *en route* (Nicholson and Forgan, 2013).

ESC ships could also conceivably travel to other *galaxies*. For example, the Andromeda galaxy is expected to collide with the Milky Way in about 4.5 billion years. While Earth by then would already have suffered its final extinction due to solar expansion, it is conceivable that ESC ships had earlier successfully transported humans and Earth life to nearby exoplanets. During the galactic collision, a civilization on one of these exoplanets

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might then potentially be in a good position to launch ESC missions to any stars of Andromeda which happened to pass nearby. Alternatively, the inhabited exoplanet and its sun might be ejected from our Galaxy altogether during the collision, travel across space and subsequently be captured by a third galaxy. If appropriate EER missions were in place during this sequence, our civilization could potentially migrate to that galaxy.

It is fitting at this point to mention one last mass extinction event conceived to be even deadlier than the solar expansion event. It is predicted by most cosmologists that the universe itself will come to an end some billions of years from now. Concerning the specific manner of its demise, however, there is an odd lack of consensus. In one scenario it is supposed that the universe will suffer a 'heat death', in another a 'Big Crunch' and so on (see Mack, 2020). While this lack of agreement affords a clue that perhaps none of these scenarios is correct, other evidence suggests that the universe could actually be existing in a state of stable equilibrium, neither expanding nor contracting (e.g. Edwards, 2012). Given this state of uncertainty, the possibility should be kept open that an advanced civilization, using EER and ESC, could potentially range to the farthest corners of the universe.

Conclusions

In this paper, we have reviewed the status of AU systems for partial and complete ectogenesis and outlined their potential use in colonizing post-apocalypse Earths and exoplanets. It is concluded that insufficient research and development has yet been done on such systems to determine their effectiveness in this capacity. Numerous legal and bioethical issues would need to be addressed before these systems could be designed and fully tested. The factor of long-term stability of seeds, embryos and gametes in cryostorage is of lesser concern, since even with presently known values at least some missions of short duration (e.g. decades) would be feasible. AU systems for complete ectogenesis in EER missions would allow civilizations to leapfrog past long intervals of mass extinctions and barren landscapes to more habitable ones beyond. ESC missions would allow these same civilizations to survive and multiply on different exoplanets and thus escape major mass extinctions, including the final solar one.

Beyond the ethical issues, there is another potential stumbling block that could impede these developments. Good supporting narratives for space missions are a necessity if ever they are to be launched, as only then they can become embedded in the public psyche (see Wright and Oman-Reagan, 2018). From a storyteller's vantage point, however, there is a built-in problem with the embryo approach. The common human narratives for space travel – which tend to echo the *Star Trek* theme – all go up in smoke. How are we supposed to cheer on a cast of cryopreserved embryos to great deeds? And yet the embryo ship concept has not gone entirely without story support (Crowl *et al*., 2012; Hein and Baxter, 2019). It featured in Arthur C. Clarke's *Songs from Distant Earth*, for example, and to a lesser extent in the movie *Interstellar*. In both stories, the virtues of the embryo approach are totally undermined, however, when the narrative focus switches to *manned* space missions. Such narratives are inadequate to motivate societies to initiate EER and ESC missions. In the author's view, more suitable ones would adhere tightly to the general principles outlined herein. With suitable stories and AU technology, an advanced civilization such as ours could then weave an ever more intricate galactic tapestry of living worlds, one which could ultimately intertwine with those of other similarly inspired advanced civilizations.

Conflict of Interest. None.

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