



Original research article

Aquatic refuges for surviving a global catastrophe

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ARTICLE INFO

Keywords:

Global catastrophic risk
 Existential risk
 Refuges
 Disaster shelters
 Social collapse
 Human extinction

ABSTRACT

Recently many methods for reducing the risk of human extinction have been suggested, including building refuges underground and in space. Here we will discuss the perspective of using military nuclear submarines or their derivatives to ensure the survival of a small portion of humanity who will be able to rebuild human civilization after a large catastrophe. We will show that it is a very cost-effective way to build refuges, and viable solutions exist for various budgets and timeframes. Nuclear submarines are surface independent, and could provide energy, oxygen, fresh water and perhaps even food for their inhabitants for years. They are able to withstand close nuclear explosions and radiation. They are able to maintain isolation from biological attacks and most known weapons. They already exist and need only small adaptation to be used as refuges. But building refuges is only “Plan B” of existential risk preparation; it is better to eliminate such risks than try to survive them.

1. Introduction

Asimov (1981), Leslie (1996), Rees (2003), Bostrom (2002) and other authors have shown that multiple existential risks threaten human survival on Earth. In recent years interest has grown in the possibility of building “universal” refuges to protect from many types of global catastrophes, which could wipe out humanity. The most publicly well known of such ideas is Elon Musk’s plan to use Mars as a “backup drive” for humanity by moving one million people there in the next several decades. Jebari (2014) analyzed general design features that should be in any such installation. Torres (2016b) addressed the question of space bunkers. Beckstead (2015) provides critical analysis of catastrophes for which refuges may be helpful. But refuge creation always involves trade-offs, which Turchin listed in his “Map of Shelters and Refuges from Global Risks” (2016).

Several works of fiction have explored the use of submarines as refuges, including Shute (1957), Brin (1990), Brin (2013), Morrow (1995), Pellegrino and Zebrowski (1995), Brooks (2007), and Stephenson (2015).

And yet despite these fictional accounts (and no doubt more could be added to the list), a formal investigation to the use of submarines as refuges has hardly begun. In their recent article reviewing the topic Baum, Denkenberger, and Haqq-Misra (2015a) wrote: “Aquatic refuge design has received virtually no attention and could be the subject of a dedicated analysis” (2015). We will try here to make the first steps in such an analysis.

We will concentrate on both the larger perspective of the general use of submarines as refuges, as well as on one practical near-term example: the conversion of an Ohio class submarine into such a refuge. The first reason that Ohio class submarines are ideal for this role is that they are the largest submarines currently in the US Navy (the Russian Typhoon class submarine is twice as large, but are retiring and only one is now in service, compared to 18 Ohio-class). They support a large crew of 155, and can hold thousands of tons of supplies (enough for 5 years, detailed in Section 4.1). Ohio submarines have special hatches for quick replacement of supplies

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and their projected time between major overhauls is 15 years.

The second reason is that Ohios are strategic ballistic missile submarines (SSBNs), which means that they are designed for long-term lone survival, while attack nuclear submarines typically have less endurance and always have smaller size. They are designed to survive a large-scale nuclear war. The US Navy also has a relatively strong safety record and greater experience than other submarine forces.

The third reason is that the Ohios will start to decommission and be replaced in 2029, so at that time some of them could be refurbished into refuges for fraction of cost of new submarines. Ohios are among the most sophisticated existing submarines, implementing the best technologies. Ohios can endure 3–6 months underwater, and their reactors can run 15–20 years without refueling (actual performance is secret). The next generation of US SSBNs – the Columbia class – will be even larger, and its reactor will be able to operate for 40–50 years without refueling, while Ohios require refueling in the middlelife (Lundquist, 2011).

We also will look at designs for aquatic refuges which might be implemented in the more remote future. They are not fantasy, as they could be built with the same money and research as the International Space Station, but they would require decades of work. Consequently, they are too expensive and too remote in the future to act as refuges from current risks. These futuristic designs also could become obsolete before they are ready if new global risks appear, and they will have an opportunity cost by attracting precious money and resources from other underfunded projects such as biosafety and the development of safe AI.

Such cost-benefit analysis shows that use of existing military submarines as refuges with small changes provide the greatest utility gain in existential risk prevention, and among available possible options, Ohio class submarines are the best candidates.

2. Stages of project realization: near-term and long-term

By utilizing existing military submarines and submarine-building technologies we can radically reduce the cost of building global catastrophic refuges. Military submarines are already optimized for most functions of x-risk refuges.

The project could be realized on two levels: near-term (realistic) scenarios and long-term (futuristic) scenarios. The first levels could be completed now or in the next 10–15 years with modest investment and based on existing technologies. The later levels would require larger monetary outlays and will take decades, but are still technically feasible and would be less complex than creating a base on Mars.

Given these factors, it seems rational to realize the early stages, but probably not the later stages, as they will be too expensive and remote. Table 1 lists these stages with their relative costs for easier comparison. These costs and times are just preliminary assessments based on current submarine building practices.

2.1. Near-term, realistic scenarios

- 1. Current level, military submarines.** Currently, there are around 130–150 active nuclear powered submarines in the world, about 75 of which are in the US Navy (as of 2014), 45 in the Russian Navy (though many of Russian submarines are not active, because they are awaiting extensive renovation), 13 in the UK's Navy, 10 in the French Navy, and 10 in China's Navy (Global security, 2017, World Nuclear Association, 2016). Of the total, around 38 are large SSBNs and of them 18 are Ohios. In any given moment in peace time only a few submarines are on a patrol in the ocean, as they need frequent maintenance in docks. The information about submarines at sea is quickly changing and highly classified so we can only guess that at any given time only a half are at the sea, and US has the highest level of sea presence, so there are 35–70 nuclear submarines in the sea at any given moment. The US navy allowed women to serve on submarines in 2010, and in 2016 50 female crewmembers were selected for service on Ohio class SSBNs (LaGrone, 2015). However, because each submarine has two separate crews, only a few females would be on each, and most of them would not be at sea at any given time, so this level is not enough to permit a sustainable population. More female crewmembers will be allowed in 2020 for Virginia class SSNs. The British Navy also started to add females in submarines crew in 2015 (BBC, 2014). So current nuclear submarines could become refuges in the case of a global catastrophe, but only incidentally, and not very effectively, if the goal is to rebuild a self-sustaining civilization.

Table 1

Time and price of various stages of project realization.

	Current level military submarines	Additional mission for military subs	One old submarine rebuilt into a refuge	A new specially design submarine refuge	A very large generational submarine "Ark"	A fleet of around 10 special sub-refuges	The same fleet plus each submarine has its own port island	Future high-tech subs
Time of surface independence	3–4 months	4 months	6 months	2 or more years	10–100 years	2 or more tears years	50 years	Hundreds of years
Number of people	~1000	~1000	100–300	200–500	2000–5000	2000–5000	2000–5000	embryos
Number of submarines	10 in the sea	1–10	1	1	1	10	10	
Price, USD	0	1–100 mln	~1 bln	2 bln	20 bln	100 bln	200 bln	
Date, earliest possible	Now	2020?	2025	2030	2040	2040	2040–2050	After 2050

2. **An additional mission for military submarines.** A small upgrade to existing military submarine practices would allow for greater catastrophic risk preparedness: adding more female crewmembers, educational books, agricultural seeds, and several tons of additional equipment for survival. If in the next few years half of the crews of most submarines in the world were female, and the crews will be instructed to prepare for survival after a possible global catastrophe, it would create 20–60 refuges against existential risks with relatively minor additional cost. Large numbers of refuges would provide additional protection. But none of these submarines would be prepared for long term survival, potentially years. However, they could possibly help each other, though this has its own risks, like biological infection. On these first two levels, submarines serve both military and refuge goals. On the next levels submarines work only as refuges, but existing military submarine shipyards and technologies are used to build them.
3. **One old submarine rebuilt into a refuge.** Many submarines are going out of service, and some of them may be in good technical condition despite military obsolescence. They may be too noisy or not adapted to existing types of weapons. Such submarines might be re-commissioned for civilian use, all weapons and secret equipment stripped, and the freed space filled with food, seeds, and other equipment. This may cost between 100 mln – 1 billion dollars; a substantial savings over building a new submarine. We suggest painting it yellow to emphasize its peaceful purposes. It might also constantly send an acoustic or other signal, which will help to distinguish it from military subs in case of war (yet it should be able to switch off this signal, as in some catastrophic situations it would be preferable to remain concealed). Its operation and crew should be international, originating from the largest rival world powers, and they should be partly scientific, though it would most likely still need some ex-military officers for command and reactor operation. Perhaps it should sail under the UN flag, which would give it a better chance of independent survival. It may coexist with the military submarine refuges described above.

2.2. Long-term, futuristic scenarios

1. **A new specially-designed submarine-refuge:** If more money were available, a new submarine specifically designed for the purpose could be built. It should have the following characteristics: long independent survivability; a very strong titanium hull for diving to 1 km or more; large storage space; large crew; food growing and harvesting capabilities; and a second nuclear power reactor and redundancy of other critical systems. Attachments for submarine drones and a hangar and a flight deck for flying drones could also be crucial. Relatedly, as lack of volume is a primary concern for submarine refuges, Brin (2016) has suggested dividing refuge submarines into two parts: a mobile (normal) submarine and larger moored submersible base. The first will provide energy, transportation and survival in the acute phase of a catastrophe, and the second will provide a larger volume for long term survival of larger numbers of people, as well as supplies, food, equipment for farming, and so on. The moored portion might also be unmoored and towed (submerged or surfaced) to other locations as needed. (This idea could work with several of the scenarios proposed here).
2. **A very large generational submarine “Ark”.** The larger a submarine, the longer its potential independent survival. An ark submarine would be analogous to the idea of generation starships, which take hundreds of years to reach other stars (see Hein’s recent analysis (2012)). It could be fitted with animals and an even larger crew, perhaps thousands of people, and should be able to survive independently for decades. Such a vessel would stretch existing shipbuilding technologies, being perhaps 20 times larger than the previously built largest Russian subs, and may be vulnerable because of its size, but it seems technically possible. Its price may be as high as 100 billion dollars, more than the price of the most costly aircraft carriers, but cheaper than the international space station or a Lunar base (Sabathier, Wepler, & Bander, 2009). Such a vessel might help in a situation where the initial impact of a catastrophe is not high, but subsequent contamination is very long term. It could also be thought of as like a mobile submersible seastead, and if seasteads were ever made, this would become a possible next step.
3. **Fleet of around 10 specially-designed submarine-refuges.** In contrast to one giant ark, a larger number of smaller submarines may increase survivability, due to the stochastic nature of some natural catastrophes, whose effect could have unpredictable variations on the Earth’s surface. This could also provide the opportunity to test several designs, adapted to various types of catastrophes. Some small and strong-hulled titanium submarines could survive stronger impacts and tsunami waves, but larger submarines with thinner hulls could be better adapted to long-term survival in a contaminated world. The fleet will also provide a chance to safely renovate some of the submarines or replace crews, without losing their presence in the sea. Such a program will cost around 100 billion dollars and will take decades to realize. It will also provide jobs for shipyards, putting a similar level of stress on the economy as military programs; this could even be beneficial in Keynesian economy logic.
4. **The same fleet plus each submarine has its ‘port island’.** The next logical upgrade for the program would provide each submarine with a “port island” with docks, stocks, and fertile grounds, as an easier starting point for rebuilding civilization. Such an island should be non-human populated, and far from civilization. Possible examples of such islands could be some of the Pacific Islands, Alaskan Islands, *peri*-Antarctic islands like Kerguelen and South Georgia, and so on. The reason for the island port is that there are two stages for many types of catastrophe, the impact stage and contamination stage. (There is also the possible stage of “secret contamination” which may apply to some slow bioweapons similar to AIDS.) The requirements of these two stages can be quite different. The first may require, for example, a strong hull, and the second might require strong decontamination ability and/or the ability to wait, potentially for many years. In any case, each submarine should have clear instructions on how and where it will start to rebuild civilization. The submarine could provide nuclear-powered electricity during initial rebuilding and a shelter if conditions worsen temporarily. It could be used as transportation to other regions, which will be able to connect survivors. Island-plus-submarine is likely a more viable solution than submarine alone.
5. **Future high-tech submarines.** In several decades the role of robotics, AI, nanotech, and genetically modified organisms will

grow, and these new capabilities could be used to build more sophisticated shelters. This may result in the use of manufacturing robots and partly self-replicating robots for the construction and population of the sub-refuge. Frozen gametes and embryos, and even artificial uteruses, may become possible. Narrow AI could control the process and guide recovery. These emerging technologies associated with risk adaptation would themselves have associated risks and ethical problems worthy of consideration (Green 2014, 2016).

This temporal and technological progression would hopefully result in cheaper, larger and more durable submarines. Also, the creation of subs will provide needed expertise in the planning of space bunkers, as suggested by Torres (2016b).

3. Advantages of nuclear submarines as refuges

Nuclear submarines are designed as very robust survivors, and humanity has 60+ years of experience that allows us to build submarine refuges by applying our accumulated knowledge. Nuclear submarines are surface independent, and could provide energy, generate oxygen from water by electrolysis, generate fresh water by desalination, and carry large food supplies for its inhabitants for many years. They are able to withstand close nuclear explosions and radiation. They are isolated from biological attacks and resistant to many weapons. They already exist and need only minor adaptations to be used as refuges. So it seems reasonable to consider using them as such.

3.1. Technical advantages

There are two types of advantages, technical and social. First we will discuss technical.

Nuclear submarines are designed to survive high pressure, explosions, to be surface independent and produce fresh water, oxygen and power, and to survive long periods without any support from civilization.

They are also optimized for hiding. This feature is less important for survival from natural catastrophes, but several risk scenarios are imaginable where secrecy will be useful.

Next, unlike other types of refuges, submarines are mobile; they are able to move all over the world's oceans. As we do not know the full range of types of future possible catastrophes, it may be useful to be able to move unobtrusively to various locations where chances of survival will be higher.

Submarines do not have nuclear power heat dissipation problems. The best way to provide long-term power for a refuge is a nuclear reactor, but most terrestrial reactors need a cooling system, which contradicts the requirement of surface independence. There are possible solutions for such terrestrial nuclear power plants, like using surface water, ground water, long pipes in surrounding rock or building them in ice. But a submarine exists in a cooling liquid, which is optimal for heat dissipation.

The average water temperature in global oceans is around 6C, and the thermal inertia of the oceans is high. If a brief period of extreme global warming were to happen, the oceans would still be cold enough for survival for many years. The oceans also would dilute the concentration of any dangerous chemicals and radioactive elements, while providing a source of oxygen and drinking water.

Submarines effectively can go deeper than underground bunkers. The ocean has median depth of 4 km, and a maximum of 11 km, and, unlike land, is cold even in the deepest places. In comparison, subterranean bunkers suffer from a geothermal heat gradient of approximately 25C per km (Fridleifsson et al., 2008), and so (depending on depth) could require sophisticated cooling systems. This makes bunkers deeper than 1 km extremely difficult (as surrounding rock could be 40C or more), especially surface independent ones. In contrast, the Russian titanium-hulled submarine "Komsomolets" could dive to 1250 m and the Russian submarine "Losharik" might be able to dive to 2 km and may be more (Global security, 2016).

The importance of submarines' ability to go deep underwater is shown by the risk from cosmic ray bursts. Dar, Laor, and Shaviv (1997) suggested that the merger of neutron stars could produce intense cosmic ray bursts, which result in extinctions approximately every 100 mln years. Such bursts produce muons, which could yield 100 times the fatal dose of radiation on the Earth's surface, and may be able to go up to 3 km underground or underwater before their intensity will diminish to 1 per cent, and approach a level tolerable to humans. Such bursts might also radiologically activate iodine and other elements, which would affect shadowed regions of the Earth.

Cirković and Vukotića (2016) has suggested that to survive such a burst one would need to construct bunkers 3 km deep. But because of high underground temperatures such bunkers may be possible only in ice (where the pressure problem will exist, as ice is amorphous and moving) or in rock near ice (such as under Antarctic mountains). In contrast, creating a submarine capable of withstanding 3 km depth is possible. It also would be able to move to parts of the ocean where the gamma-ray source is in the Earth's constant shadow or near the horizon, thus effectively increasing its depth.

3.2. Social advantages

Social advantages include easy construction, usage and participation in global risks prevention.

The required technology for building submarines already exists compared to suggested space refuges on space stations, Mars or the Moon. Existing nuclear submarines could be used as refuges even without interruption of their military duties, with low cost upgrades (that is adding female crewmembers, some supplies and training, more below). The construction technologies and production yards are proven, and we already have the necessary skilled workers. So construction would have no major technological

surprises.

Next, submarines will be less accessible to “hostile survivors” who may try to break into the refuge after the start of a catastrophe and bring dangerous viruses or contamination within, or otherwise cause harm.

Because refuge submarines will be filled with dedicated humans, knowledge, and supplies, they could become “centers of crystallization” for future human civilization, and the seed of the rebuilding process. Even if thousands of people survive a catastrophe, they will be scattered over the Earth surface. Unprepared, isolated, and injured, they may be doomed to extinction. Yet in this situation, a small group of highly qualified organized survivors with needed supplies would be very helpful for starting civilization again and helping the other scattered survivors (though if the catastrophe is biological such contacts pose risks).

It is unlikely that such a submarine would be available for a hostile agent who may want to create a global catastrophe and be the only survivor, or leverage the risk of a global catastrophe for global blackmail, as such submarines will be available only to large state actors and even international groups (this is not so in the case of underground bunkers, which anyone can dig). However, some dictators or billionaires could use submarines as personal refuges and even pay for their construction, the same way as they pay now for personal bunkers.

Much of the time submarines will be isolated from dangerous information sources, including computer viruses and cyberattacks by narrow AI.

Submarines would also help to create a professional class of people who exist to mitigate existential risks. While they are on the submarine they can engage in natural and social scientific research, policy research and advocacy, culture building, etc.

The combination of social and technical advantages makes submarines an attractive type of refuge against a wide range of global catastrophes.

4. Possible counterarguments for use of nuclear submarines as refuges

Here we will address possible counterarguments against the project and ways to reply. These counterarguments also can be divided into technical and social.

Technical counterarguments involve dealing with the physics of the water medium, submarine technical characteristics, the possible impacts of the catastrophes, and maintenance in a marine environment

4.1. Arguments that submarines will not be able to survive long enough independently

Despite various claims that nuclear submarines may stay years underwater, actual maximum known underwater duration is only 3 months. There are several reasons why longer underwater missions are problematic and we will now analyze them.

First, most submarines require regular extensive maintenance in docks. Such maintenance would be very difficult or impossible after a catastrophe. But the mode of use of a refuge-submarine will be rather different than the use of a military submarine. The military submarine secretly circles the ocean. But a refuge-submarine could be stationary in deep water not far from its port, which will result in much less wear on its engines. After a catastrophe, in most scenarios, it also would not need to stay under water for years, but could remain on the surface. Regardless, specially built refuge-submarines should be provided with inbuilt redundancy of critical elements, and with self-repair capabilities. The latest British submarine is claimed to be able to stay 25 years under water (BBC, 2014), but has to surface every three months to replenish its food supply. While the food problem seems to be fixable the main problem would be equipment breakdowns, which may require dock-fixing. Even though a 50 years lifespan is now reachable for a nuclear reactor, and most contemporary submarines carry spare parts for ongoing repairs and maintenance, there could still be need for unexpected major repairs. A refuge-submarine would need to carry an even larger stockpile of space parts as well as very high quality metal 3-D printers to manufacture any parts not on hand.

Second, seaweed, barnacles, and marine life damage submarine hulls. Submarines require regular docking to clean their hulls and stop corrosion. There are two types of repairs: medium overhaul, which is typically done once every several years and mostly intended to remove corrosion, and large overhaul, which includes replacing many parts and refueling the nuclear reactor. After a catastrophe, neither type of overhaul would likely be possible. With current technology, it looks as though five years is the maximum time of viability of a submarine without overhaul in port. In the future, remote-controlled repair drones might be able to somewhat extend this viability.

Third, carbon dioxide accumulation is a constant problem for submarines. Submarines typically get rid of carbon dioxide by a chemical reaction which uses non-renewable chemicals. Many tons would be required for years of survival and this would waste precious storage. But new technologies are being developed to clean carbon dioxide from the air without relying upon non-renewable chemicals; either by dissolving carbon dioxide in seawater (Coxworth, 2010) or using renewable nanomaterials (Stockton, 2014). Other technologies exist that are used in space. Another possible solution, if given enough space, would be to use plants to harvest carbon dioxide onboard and produce food.

Fourth, submarines have limited storage for long-term isolation, especially food. NASA rations are currently 1.7 kg per person per day, and there will be other needed supplies, such as medication, survival equipment, clothing and spare parts. Therefore, it might be safe to estimate that on average 5 kg of materials might be needed per person per day, though it may be much lower, perhaps 2–3 kg/day. (But it could be as small as 600 g of dry rice which has energy content of 2100 kcal.) Baum, Denkenberger, Pearce et al. (2015b).

Returning to the Ohio class submarine example, each Ohio has a crew of 155 people and carries 24 UGM-133 Trident II missiles each weighing 59 tons, equaling 1416 tons total. If just the missiles were replaced with food and other supplies, then based on the above usage estimate of 5 kg per person per day, it will provide supplies for 1827 days, or exactly 5 years.

4.2. Arguments that submarines are not effective as refuges

There are some reasonable arguments that submarines are inadequate refuges which would not guarantee human survival, but only provide a small chance of it. It is not easy to give numerical estimates of such a chance of survival but it might be safe to say (depending on the specific event) that it is between 1 and 10 per cent.

1. **Not universal protection.** Most future catastrophes will be either too small or too large for dedicated refuges to be useful, as has been shown by [Jebari \(2014\)](#). The most serious risks to humanity come from emerging technologies, including biotechnology, nanotechnology, and artificial intelligence, and such 20th-century style systems as nuclear submarines will provide little defense against them. Refuges will also not be of use if the biosphere is severely damaged, and does not return to normal within 10–50 years of a catastrophe, which could happen in the cases of runaway global warming, some broad-spectrum synthetic biological pandemics, global radioactive contamination, or a large bolide impact or a flood basalt event.
2. **The ocean could be affected by high tsunami and/or pressure waves** in the case of a large asteroid or comet impact. Most current submarines can survive at a depth of 400 m, so they might survive long pressure spikes created by the waves above them as high as 200–400 m, but not kilometer size waves. Submarines are also designed to withstand short pressure spikes from close explosions of deep charges and even nuclear explosions. Energy of shock waves is inversely proportional to the square of the distance ([Costanzo 2010](#)), but the open question is if underwater shock waves will decline quicker than surface waves. Recent simulations of asteroid impacts in water ([Patchett, 2016](#)) showed that waves' size depend on many factors during an impact. Another research suggested that pressure waves could contribute to the marine life extinction during asteroid's impacts ([Takayama et al., 2016](#)), but numerical simulation showed that such waves will be attenuated by surface unloading. However, wave guides could form in water depth, which means that a submarine should stay in the shallow waters if passing of such pressure wave is expected. However, the Russian-built titanium 1980s submarine "Komsomolets" could dive to 1250 m ([Taras, 2006](#)) and Russia also now has a submarine "Losharik" with a working depth of at least 2 km or possibly even 6 km ([Global security, 2016](#)). Also, a submarine could be stationed in a basin like the Mediterranean Sea which would probably be less affected by an oceanic tsunami. The probability of bolide impact upon the Mediterranean Sea is 1/200 of the total probability of a bolide hitting the Earth. If there are several deployed submarines and they are widely distributed around the world, it is more likely that some of them would survive an impact event.
3. **In the most plausible scenarios of catastrophes, more people will survive on land, than on submarines.** Even if a catastrophe had the intensity to kill 999 of 1000 people, millions of people would still survive on land. However, initial survival may mean nothing if the impact stage is followed by long-term contamination and high fatality rates. In any case, submarines could become centers for preserving knowledge and civilization, and coordination and communication with other survivors.
4. **One of the weakest parts of the submarine project is humans.** To be placed seemingly forever in a deep enclosed space exerts strong pressure on the human mind, which may result in dangerous behavior and/or suicide. Navies, airlines, and other groups are fairly good at sorting out unstable candidates, and if such work becomes a channel for getting into space or another similar benefit, it will attract top-level applicants. Before a catastrophe crews may be rotated the same way as the rotated in current SSBN, that is every 3 months, and as no accidents of mass psychosis on board is known, it means that effective technology of psychological training exists. It includes careful choosing of the crew members as well as some forms of entertainment on board, including high quality food, movies, and exercise facilities (Ohio has treadmills and a well-equipped kitchen). If a catastrophe happens it will put enormous stress on people on board as most their relative will die and because of large uncertainty about their own survival. Large group of relatively young people of both sexes confined in small space will be prone to internal conflicts which could undermine survival of the submarine. But the problem is a general one, which would happen in space stations, underground bunkers and almost any other types of refuges.

4.3. Is one submarine crew enough to rebuild human civilization?

This question aligns with previous question of the effectiveness of submarines as refuges, but is in fact wider, because it is applicable to any type of refuge. It is related to questions involving the most effective sex ratio in a refuge, advanced reproductive technologies, and future questions involving the proper numbers of offspring. It may require special analysis by geneticists, demographers, and other researchers. But, in general, we think there is already adequate evidence that one crew could be enough to rebuild human civilization, but not guarantee its survival, as during the catastrophe and after coming ashore the crew could experience many unpredictable events.

The crew of an Ohio class submarine is 155 people. Evidence based on genetic variation suggests that groups of around 70 people colonized Polynesia and the New World ([Hey, 2005](#); [Murray-McIntosh, Scrimshaw, Hatfield, & Penny, 1998](#); [Hanson, 2008](#)). This means that inbreeding was a soluble problem, possibly because women had many children which permits rapid selection.

Inbreeding could be partly solved by using genetically diverse frozen sperm and eggs, and/or frozen embryos, and *in vitro* fertilization. *In vitro* fertilization often results in multiple births, which means that a smaller number of women would be needed to birth many children in the first generation, but highly trained medical professionals would be necessary.

In vitro fertilization provides for reproduction in older ages, so if a submarine spends less than 10 years under water (likely, given other constraints), reproduction onboard the submarine would be unnecessary. Additionally, the crew, embryos, and/or gametes, should be genetically diverse in order to lower the risk of inbreeding. Some studies show that inbreeding with first cousins increases the rate of the birth defects 1.3 to 1.6 times compared to the background level of 3 per cent (that is to 2–5 per cent, equal to risk for

women after 40). So it could be an existential risk for a post-catastrophe human colony if it will have high fertility rates (Bennett et al., 2002). Repeated consanguineous marriages in Pakistan have resulted in the doubling of infant mortality (Bittles, 1994), which is not good but acceptable for human survival. Consanguineous couples have higher fertility rates, which has social, but not biological reasons, and it may be helpful in restoring human population (Bittles, 1994; Helgason et al., 2008).

Ecologists often use the “50/500 rule”, which states that minimum number of organisms needed to survive a population bottleneck is 50 (because below that it will happen inbreeding depression), and to survive long term it is 500, as that is needed for evolutionary adaptability (Frankham, Bradshaw, & Brook, 2014). But this rule includes only fertile individuals, and not children, the elderly, or other members of society, so the actual number for a minimal population will likely be higher. A submarine refuge’s initial crew will consist mostly or exclusively of fertile individuals, but over time the number of fertile individuals will decline.

Lastly, any small accident could easily bring this number below critical levels, so while one submarine might be able to prevent extinction, the possibility is not assured.

We could consider clusters of multiple submarines as a means of expanding survivor populations, which seems possible as dozens of military submarines are always at sea.

4.4. Arguments that creation of the submarine refuges is not the best strategy for approaching the problem of existential risk

Even if submarine-refuges might work, large-scale projects have opportunity costs. If a large submarine refuge project were started, money and global attention could be diverted from other more cost-effective, perhaps overall better projects, such as asteroid defense or the creation of friendly AI. Therefore, this should be carefully analyzed in comparison with other mitigation and adaptation strategies.

Another danger is that later stages of the project could become obsolete before completion. A completely new submarine refuge project would take 10–30 years of planning, funding, and construction before becoming fully operational. During this time many new technologies will appear, which will each create new risks. So submarine refuges work best in an environment of slow technological development and low-tech risks. Therefore, given contemporary circumstances more quickly adapting existing military submarines with smaller changes would probably be most effective means of creating submarine refuges.

5. Comparison with subterranean and space bunkers

The best standard for refuges against existential risks is surface independence. The two main types of such refuges which have been discussed in previous literature, are underground bunkers and space refuges (there are other type of refuges which are not surface independent, such as private bunkers, ships at sea, Antarctic bases, remote islands, etc., but they are outside the scope of this article, as they are not surface independent).

Of all underground refuges the most attractive are nuclear bunkers like those built in the Cold War, since they already exist and provide all the necessary equipment to survive a large-scale catastrophic event. Their main disadvantage is that they will be targeted in the case of war, and as their locations are known, they will be much easier to target than submarines. They cannot move, so they cannot escape some types of catastrophes. But they can house more people and distribute them widely in complex network of tunnels, with large amount of goods, etc. Unfortunately, the Earth’s thermal gradient prevents these bunkers from being both very deep (more than 1 km) and surface isolated at the same time. Additionally, hostile survivors might easily attack them. Future bunkers could be built in such places as Antarctic mountain ridges or as large networks of tunnels. Using submarines as refuges does not mean that bunkers should be ignored, as the best protection is offered by diversification.

Future space refuges, which include space stations with same number of people as in a typical submarine, or Moon or Mars settlements with even larger number of people, could provide dramatically greater Earth-surface independence. But they are much less mature and require much more expensive technology. Their starting price is probably above 1 trillion dollars, (as the price of the ISS is more than 100 billion dollars, and it able to support only 6 people for 3 months (ESA, 2013)), while 100–300 billion is the end price for building of even the most sophisticated submarine-refuges (for example, 6 billion dollars is the price of the newest, most sophisticated Columbia-class submarines in the US fleet (O’Rourke 2016)). Submarine refuges could help prepare people and technology for space refuges. Their main disadvantage is that they do not yet exist, will require decades to build, are much more expensive, and will be no less vulnerable to accidents or hostile acts as submarines. The problem of their self-sufficiency is not solved, so the survivors would eventually need to return to Earth. These settlements could become competitive with submarines in terms of price and safety when new types of space exploration based on emerging technologies appear, but these new technologies will themselves bring new risks.

Submarines seem to have the best combination of advantages, as they combine the isolation of islands and Antarctic bases, and surface independence similar to space bunkers, with the relatively low price and high viability of land bunkers. Additionally, their technology is well-explored and their mobility is something no bunker can offer. Ideally, all protection systems should work together.

6. Types of catastrophes where submarines may help

6.1. Probability that submarines-refuges will prevent human extinction

Many ideas about possible sources of global risks have been suggested (Freitas, 2000; Posner, 2004; Rees, 2003; Tonn & MacGregor, 2009; Torres, 2016a, 2016b). Beckstead (2015) wrote that most types of catastrophes are either overkill or

underkill for refuges to be useful.

For example, consider bolide impacts as a (admittedly imperfect) guide for the size distribution of the future catastrophes. Asteroids of ~10 km size are 30 times more rare than ~1 km size (Napier 2008). And 100 km bodies are even 30 times more rare than 10 km. Assuming that 10 km is sweet spot where submarine-refuges could help, and 100 km will result in extinction anyway, we get the following distribution: roughly 97 percent of impact cases are underkill, 3 per cent could be saved by the submarine-refuges, and 0.1 per cent cases are overkill. The non-linear distribution of asteroid sizes favors underkill events. This is just a quick calculation, as for some types of catastrophes such tail distribution does not work. Even in situation of “underkill” submarines may be useful as they will help in coordination of survivors and make reconstruction of the civilization more rapid and probable.

Some types of futuristic catastrophes are always overkill, for example malicious artificial superintelligence, which is regarded by many specialists as a most serious risk (e.g. Bostrom, 2014). Submarines will not help in some other scenarios previously identified by existential risk researchers, e.g.: runaway global warming, accelerator accidents where small black hole may appear (Kent, 2004), and grey goo of self-replicating nanorobots (Phoenix & Drexler, 2004).

Even if submarines are deployed, some errors or accidents could prevent their effective use as refuges, or result in failure of their attempt to rebuild civilization.

Perfecting these estimations could be helpful for calculating the cost-effectiveness of building submarine refuges as compared to other mitigation and adaptation strategies.

6.2. Catastrophes types

Beckstead (2015) has argued that two types of catastrophes could make refuges useful: pandemics (Doherty, 2013) or a cobalt bomb (Kahn, 1960), and has also argued that both scenarios are not very plausible.

We disagree that refuges are effective against such a limited number of types of disasters and we also think that Beckstead underestimates the risks of pandemic and radiological contamination, as they may become much more likely due to the appearance of new technologies in next 20 years.

Artificial pandemic. The danger of an artificial pandemic created by means of synthetic biology is much larger than that of any natural pandemic. Indeed, it will likely be one of the highest catastrophic risks in the 21st century. Pandemics may be designed by hostile agents to deliberately kill everyone on Earth. Or it might take a form of a multipandemic, where many different agents would be released simultaneously (Turchin & Green, 2017)

Radiological contamination. The danger of global radiological contamination due to a nuclear war targeting nuclear power stations or the use of cobalt bombs is likewise serious. Russia recently returned to the project of building cobalt bombs in the form of a project on a 20Mt nuclear torpedo called “Status-6” and other such projects may exist in secret. Some natural events such as very large solar flares, gamma-ray bursts or close supernova explosions may hypothetically produce radiological contamination as well. In these scenarios, ocean water has 400 times more mass than air in the atmosphere, and any radioactive elements will be strongly diluted, so submarines in the ocean will be much less affected than anything on the surface. A nuclear war scenario with an extreme nuclear winter might cover much of the oceans in ice, but submarines could exist under it.

Narrow AI virus affects a robotic army. In the future, billions of robots will be connected by the internet of things, and militaries will be full of drones of all sizes. Computer viruses, perhaps developed by militaries, may come to have elements of AI, so it is imaginable that such a virus could make all moving robots (including self-driving cars, home robots and military drones) attack people. Such a mutiny would die off after energy and manufacturing ability is exhausted, but military level submarines could survive it in deep remote parts of the ocean. However, most in the AI safety crowd think that superintelligence is more probable and dangerous than a virus in a robotic army (Bostrom, 2014; Yudkowsky, 2008).

Short term runaway global warming. Submarines could protect against a temporary elevation of Earth’s temperatures to the 50–70C range. One way this could happen would be via the abrupt release of methane from Arctic permafrost, methane clathrates in the oceans, or a nuclear summer. To survive such a situation, a submarine would stay deep underwater, as only deep water might be cold enough to maintain reactor safety; it may even have to search for cold spots.

Bolide impact. This is a much less likely event and the bolide needs to be of an exact size, probably 1–10 km, for submarines to be useful. Such an impact would create large shockwaves and tsunamis, followed by an “asteroid winter.” This winter could cover much of the sea in ice. It could also be combined with poisoning of the atmosphere by various gases, including CO₂, sulfur, nitric oxide, and “volcanic” dust. Submarines could also be very useful during a period of bombardment with many small comet fragments, if such event were to happen (Napier, 2015).

Flood basalt event. A large volcanic event on a scale larger than a supervolcanic eruption, might change atmospheric composition and global temperature. While no flood basalt events have happened on Earth in human memory, they have been relatively common during parts of Earth’s geologic history.

Poisoning of the atmosphere may be because of oceanic anoxia, volcanic gases or artificial chemicals created by malevolent agent.

Gamma-ray burst. As noted above, a gamma ray burst could potentially cause deep sterilization of large areas of the Earth’s surface, even killing up to 3 km underground (Dar et al., 1997). But submarines could relocate to parts of the Earth where the gamma emitter will not be visible, or will be low on the horizon.

Something unknown. As the number of ideas of possible catastrophes is constantly growing, it easy to suggest that we do not know all possible scenarios. Submarines offer broad-spectrum protection from a wide set of risks, perhaps including unknown ones.

From the above, biological catastrophes, different forms of nuclear war and its consequences, and AI seems to be most probable

catastrophes. Other catastrophes such as a large bolide impact are less than 0.01 percent in next century. This means that submarines should be supplied with biological and radiological decontamination equipment, and their internet connection with outside world should be limited.

7. Some ways to make submarines even better refuges

7.1. Technical upgrades

Ocean water contains nutrients and plankton. Submarines could pump and filter water inside to use as food, whether directly for humans to eat, or through an intermediate species; bugs, seaweed, worms could all be grown onboard. Fishing also seems to be possible in some form, as some deep-water organisms could survive many types of catastrophe. Even direct chemical synthesis could be used to create sugars and other edible chemicals.

Underwater caches/habitats with useful goods could be created. As the inner size of a submarine is limited, it may be reasonable to stockpile useful goods, including food, medication, spare parts, etc., outside, but not within reach of the outside world. The seafloor could be a suitable place.

A satellite communication system would be helpful, as good information will be precious after a catastrophe. The nature and the extent of the catastrophe will probably not be clear for the submarine refuge dwellers. Images from satellites, sea and air drones, and communication with space stations and land bases will provide this valuable information and will help the crew to determine the best course of action.

7.2. Crew and social organization

In general, the problem of the crew preparation for long-term existence in confined space is solved by military psychologists as well as for long space mission (Vakoch, 2011) as we could judge from lack of known crew riots on submarines (while in the past riots on ship were common).

The most important part of this project is the people involved, and training them will be as important as building a technically robust submarine. Such preparation should consider several factors.

The preparedness of the crew is vital for the survivability of the submarine. Crewmembers should be the best people with extensive training and excellent health (Basner et al., 2014). Such people should be well paid, and this will be significant cost of the project. Fortunately, since the crew has to be young, that reduces costs because they are just starting their careers. Also, preparation for space travel is another form of “payment,” not to mention the pride of being one of the few people given the opportunity to save the world. There is a clear trade-off between being well-trained and being young enough to still reproduce well. This is a particularly acute problem for women. One solution could be that small part of the crew will be older and with higher expertise, probably ex-military officers, including the commander, nuclear specialists and other specialists needed for submarine maintenance and navigation. The other part of the crew could be young men and women who would cycle through the program over time.

After a catastrophe there could be survivors on the land, on ships, or in underground bunkers. The submarine may work to rescue and transport them to safer places and for coordination of civilization rebuilding efforts. This training can be practiced ahead of time as part of disaster response efforts, or as part of crew rotations.

The submarine should preserve digital copies of cultural and scientific information. Such information will provide education and entertainment for people inside the submarine.

Exercises in civilization rebuilding may be needed. We do not know much about the necessary conditions for rebuilding civilization, so it would be beneficial to experiment with such in training exercises on an island.

Even if the submarine project does not work out, its attempt may help to change human values and thus improve the trajectory of human history.

7.3. Preparation to rehabilitation of the land

All submarine as refuges project make sense only if some habitable land survives, where humans could start new civilization. Such land should be able to support some type of agriculture and be safe enough for human survival.

To be well prepared the submarine needs:

- Knowledge in form of physical books about history, technology and practical knowledge about agriculture and other useful things (Dartnell, 2015).
- Various seeds like the ones in the Svalbard vault in Norway.
- A large supply of essential tools, like knives, for use until descendants master metallurgy.
- A freezer with sperm and eggs and someone on board who knows how to do in vitro fertilization.
- High protection gear, which will be needed during first expeditions to establish habitability of the land, like “spacesuits”, dosimeters, filters, etc.
- Survival gear for establishing a colony, including hunting rifles, fishing nets, radio communication, solar power chargers, tents, some simple machinery, etc.

7.4. Survival strategy

The submarine-refuge should be prepared for use in several stages, which could be different for different types of catastrophes, like a slow and concealed biological pandemic.

- 1) **Expectation.** At this point the submarine is simply waiting in the ocean, probably in a secret location, as SSBNs do now.
- 2) **Impact phase.** At the beginning of a catastrophe, the submarine uses its survival skills, for example to survive large waves from an asteroid impact.
- 3) **Endurance phase.** In this phase the surface may be uninhabitable due to contamination, high or low temperature, or nuclear winter. During that time the crew has to establish the nature and scale of a catastrophe (which may be no trivial task). It may need to send probes to surface to take samples. Based on this information, the crew should decide how long to stay submerged and where the best places are for landing. It also should try to make contact with other survivors.
- 4) **Land search.** If they find that all humanity is lost, they should wait until surface conditions improve enough to make short-term excursions near prospective settlements and explore it by drones and expeditions.
- 5) **Landing.** It is important to find a good port for the sub, so it may dock and become the center of the future settlement, providing electricity and shelter.
- 6) **Building the initial settlement and beginning procreation.** After a settlement is established, it will be possible to start having children. The number of children should be enough to ensure quick growth of, and their proper education will be crucial or a dark age is possible.
- 7) **Recovery.** Even in the best case, 100 years after landing most of equipment will be lost, the original crewmembers dead, and the colony will still be small, perhaps around in best case several thousand people. With such small population only a primitive society is possible. In the best case nearly three hundred years will be needed to create society with a million members. At least several centuries would be needed to recreate technological civilization. So it would be important to preserve basic knowledge and important ideas, especially how to avoid global catastrophes again. The remains of the submarine may be such a reminder for future generations.

8. Conclusion: project “Yellow submarine” as a way of unifying humanity for positive goal

In the town where I was born Lived a man who sailed to sea
And he told us of his life In the land of submarines

So we sailed up to the sun Till we found the sea of green
And we lived beneath the waves In our yellow submarine

The Beatles.

In the last few decades, the world has spent trillions of dollars building nuclear submarines. The US is going to spend \$100 billion on a new strategic submarine program in the next 10 years and \$200 billion more for its maintenance.

Even if a small part of these resources were allocated to the creation of refuge-submarines, it could increase the probability of the survival of humanity within a specific range of possible future catastrophes.

Such preparation could be started using existing military submarines, such as Ohio class SSBNs, by adding some specific books, supplies, seeds, and more female crewmembers. It would not lower military preparedness and would not require a large funding allocation. As for costs, it is clear that the early stages of the project will not overstretch budgets, but could help military public relations. If more funds became available, the project could gradually grow in maturity, providing more and more protection at each stage.

Finding \$1 billion of public money for retrofitting an old submarine seems difficult in the current environment. For example, the Sentinel project of the anti-asteroid telescope only attracted funding of 1–3 million a year, despite its goal of 450 million. But the “Yellow Submarine” project could provide a new goal for the military-industrial complex, which could help it maintain jobs and government funding.

One option for crowdfunding might be to sell tickets for a place on such a submarine. While this might not be ideal for preparedness, if it managed to make such a refuge possible, it would be better than nothing. Another option could be a TV reality show created around it, thus generating revenue.

In conclusion, submarines are one of the best available options for refuges from existential risks, but refuges are not the best strategy to escape existential risks. Creation of friendly AI and international cooperation would be more effective. See more in “Plan of actions to prevent x-risks” (Turchin, 2015).

Conflicts of interest

None. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgments

We want to thank David Denkenberger, author of “Feeding Everyone No Matter What” for insightful comments, Phil Torres from the X-Risks Institute, Sergey Xarkonnen for an important conversation and Dmitry Shakhov for proofreading. Readers of the forum “sovpl” provided valuable technical input about docking and maintenance of submarines. Our special thanks to writer David Brin

who has thought for a long time about using submarines as refuges. We would lastly like to thank the anonymous reviewers for their effort and thoughtful consideration.

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