GO INCREDIBLY FAST
Engineering Note

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Abstract

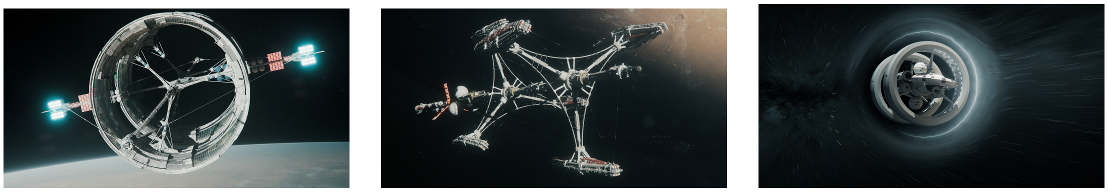
This engineering note is a companion piece to an online inspirational and educational video titled "Go Incredibly Fast" and will summarize the thinking behind the calculations used to derive the numbers quoted in the video[1]. The purpose of the short film is to identify the perennial time-distance problem of human space exploration beyond Mars and to identify a few propulsion approaches we might utilize to send humans to all the worlds in our solar system and reach out across the vast distances between stars. The spacecraft architectures highlighted in the film are nuclear electric propulsion (known physics, known engineering), fusion propulsion (known physics, unknown engineering), and finally space warps (unknown physics, unknown engineering). The short film is targeted for a broad audience with the purpose of triggering interest to dig deeper and learn more - it is thus not intended to be comprehensive. There are indeed other approaches not discussed that might be utilized to great effect to address the time-distance challenge such as solar sails, beamed energy propulsion, and anti-matter propulsion to name but a few - the film really is just the tip of the iceberg.

Keywords nuclear electric propulsion · fusion propulsion · space warp · interstellar

1 Introduction

Human exploration of the outer solar system and the stars will require significant advances well beyond the current performance characteristics representative of state of the art for spacecraft power and propulsion systems. The referenced film identifies three distinct approaches spanning what we know to what we don't know that might be utilized to solve the time-distance problem of deep space exploration. The first approach is Nuclear Electric Propulsion which is representative of a solution that is firmly based on known physics and known engineering. The second approach is Fusion Propulsion which based on known physics[2], but unknown engineering [3] The final approach is Breakthrough Propulsion which lies firmly on the frontiers of physics and explores what might fill in the gap between quantum mechanics and general relativity - so unknown physics, unknown engineering.

While there are other approaches that might be utilized to address the time-distance problem, the short film is exactly that - a short film. Further, the approaches highlighted in the film are focused on the challenge of enabling human exploration of deep space rather than robotic probes. For a more comprehensive listing of advanced power and propulsion approaches, the interested reader might consider the NASA Technology Roadmaps [1], specifically TA 2.3 Advanced Propulsion Technologies and TA 3.1 Power Generation. NASA also has the more recent 2020 NASA Technology Taxonomy[2]



(a) NEP (b) Fusion (c) Breakthrough

Figure 1: Three propulsion approaches to enable bold human exploration of the outer solar system and the stars. The left pane depicts the Nuclear Electric Propulsion (NEP) model that uses a nuclear reactor to provide power to run electric propulsion systems. The middle pane shows a fusion propulsion spacecraft that uses the fusion process to provide for both the power and propulsion needs of the vehicle. The right pane depicts a breakthrough category of spacecraft that uses a space warp to traverse interstellar distances in significantly reduced timeframes.

materials with TX01 covering propulsion systems (specifically TX01.4 Advanced Propulsion) and TX03 covering aerospace power and energy storage.

Another useful reference is the book titled *The Starflight Handbook*[3] which is a compendium of numerous techniques that might enable interstellar travel such as nuclear pulse propulsion, solar sails, beamed energy propulsion, fusion ramjets, and wormholes in spacetime (to name a few). The book titled *Frontiers of Propulsion Science*[4] explores concepts that fall on the leading edge of our understanding of physics, and numerous chapters explore current thinking on topics ranging from space drives, thrusting against the vacuum, space warps, and wormholes. For a more focused technical expansion on the concept of space warps and wormholes, the recently published book titled *Wormholes, Warp Drives and Energy Conditions*[5] provides a thorough treatment of the subject.

2 Nuclear Electric Propulsion

The first architecture considered during the video is a Nuclear Electric Propulsion (NEP) approach which uses a fission-based power source coupled to an electric propulsion system. The nuclear reactor is envisioned to be fissioning some form of nuclear fuel [4] to generate heat power which in turn drives a thermodynamic cycle to provide electric power along with unuseable waste heat. The resultant electric power is fed to an electric propulsion system that utilizes electric and magnetic fields to ionize and accelerate a gas propellant to generate thrust to accelerate the spacecraft. The waste heat is rejected to space by means of (high) temperature radiators rejecting the heat by means of thermal radiation to the cold of deep space.

The spacecraft depicted in Figure 1a from the video depicts two counter-rotating cylinders to provide artificial gravity to the ship's passengers arranged along a central-axis truss structure with two large nuclear reactors on either end, fore and aft. There is a port-starboard truss structure that bisects the axial truss structure with two large electric propulsion pods on either end along with numerous propellant tanks arrayed along the truss. There are some high temperature heat rejection systems displayed on the electric propulsion pods that would be the manner by which the noted waste heat is rejected to the vacuum of space. The ship is an artist's interpretation for communication purposes of a very large NEP spacecraft architecture reflecting these basic subsystem elements and is not meant to be a precise engineering point design of the idea.

The video quotes a transit time of 2.2 years to reach the orbit of Saturn as a flyby from Mars, and a total transit time of 2093 years to reach and capture (not a flyby) at our nearest stellar neighbor Proxima Centauri. These numbers were derived by implementing a simple model with the following environmental assumptions: gravity off; ignore planetary orbit speeds; radial trajectories. The model NEP spacecraft has a total mass m_0 of 8,000,000 kg and a final mass of m_f of 1,000,000 kg yielding a mass ratio of 8. It is assumed that the spacecraft is single stage (no staging) and that it captures at its destination of Proxima Centauri. The specific impulse used for the electric propulsion is 60,000 s[5] with an initial thrust to weight for the spacecraft of 0.00005 resulting in an electric power level of 1.15 GW with 100% efficient electric propulsion. The total thrusting time for the spacecraft is 33.3 years with a portion of that time serving to accelerate the craft prior to interstellar cruise and the

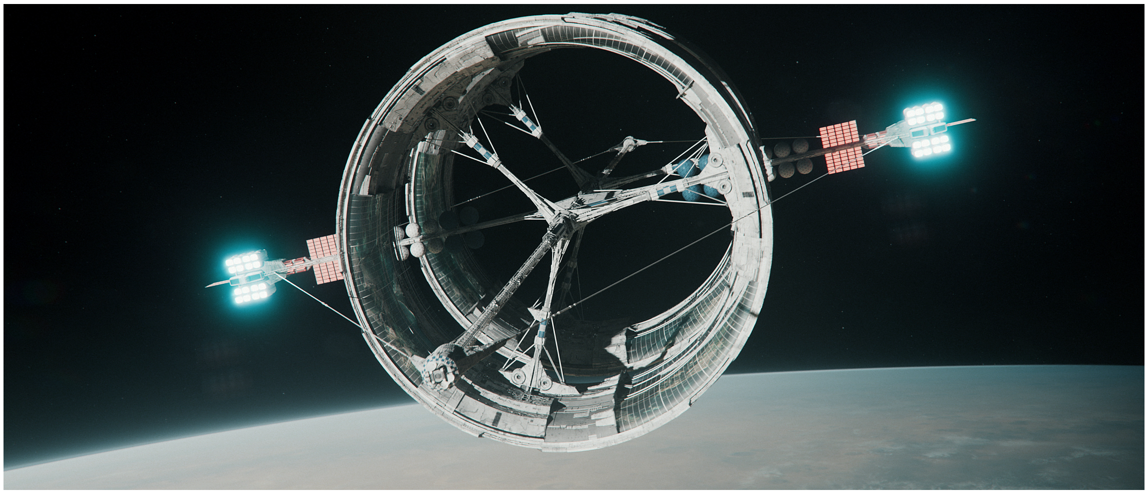


Figure 2: Enlarged view of the NEP spacecraft with the two concentric spinning rings for artificial gravity, two nuclear reactors at the fore and aft of the axial truss, and two electric propulsion pods on the port-starboard truss. Propellant tanks can be seen arrayed along the port-starboard truss and high-temperature heat rejection radiators can bee seen extending in the zenith and nadir directions from the port-starboard truss.

remaining balance of time to decelerate the craft for capture at Proxima Centauri. The peak velocity of the NEP spacecraft during interstellar cruise is 0.00205 c and thus yielding a total mission Δv of 0.0041 c.

There are three questions and one item to address before proceeding. One question that may come to mind when considering this toy NEP model is - what about staging? While staging may provide a mechanism to slightly reduce the transit time for the toy model, it is reasoned that the size and expense of an NEP-based interstellar mission architecture would necessarily not tolerate just *throwing away* colossal stages and rather require 100% re-usability. Another question might be why not consider a flyby mission rather than an interstellar rendezvous? This may be a relevant question for a robotic probe - it is altogether an illogical proposal for a human crewed spacecraft. The third question is what about the size of the toy model spacecraft versus the "worldship" scale spacecraft[6] depicted in the short film? The initial and final mass along with the spacecraft power levels can be scaled by any multiple of 10 equally and the transit times remain the same - so the model can be envisioned as a simple "lego block" spacecraft that one can scale up or down as needed. The final item to note is that while an NEP spacecraft may not appear to be ideal for interstellar transit, it does however enable humans to travel to all of the worlds within our solar system likely enabling a solar system wide society and economy. The interested reader is referred to an excellent reference paper by McNutt[6] detailing the nuclear electric propulsion performance requirements to support human exploration of all of the destinations in the outer solar system.

How close are we to this type of power and propulsion capability today? Terrestrial nuclear power is of course quite common in the world today with the footprint set to see strong growth over the next decade to help curb the world's appetite for fossil fuels and reduce global emissions of harmful green house gases. The largest nuclear power plant on the planet at the time of this writing is Japan's Kashiwazaki-Kariwa Nuclear Power Plant consisting of seven boiling water reactors with a combined electric power output of nearly 8 GW, and the globe's total terrestrial nuclear power capacity is roughly in the $\sim$ 400 GW range. Nuclear reactors are used by a subset of the worlds elite militaries to power naval vessels with power budgets of $\sim$30 MW for modern nuclear attack submarines and $\sim$400 MW for the United States latest generation (*Ford-class*) of nuclear-powered aircraft carriers. On the subject of portable terrestrial reactors, the U.S. Department of Defense (DoD) commissioned a program called Project Pele[7] with the aim of generating a 1-5 MW (electric) mobile microreactor that fits within the footprint of a 40 foot shipping container. This project is seeking to further equip and enhance the ability of the United States military to provide portable power capability to secure/remote forward bases and to provide charging capacity to an ever-growing fleet of electrified vehicles and aircraft [7]. As of April 13, 2022, DoD has made the decision to build a Pele mobile microreactor and perform demonstration at the Idaho National Laboratory[8].

The future of terrestrial nuclear power looks bright and there are efforts underway to make it more safe and portable, but what plans are there to develop space nuclear reactors? As a historical note, both the United States and the Soviet Union have flown fission-based nuclear reactors in the form of the 500 W Snap 10A, the 5 kW Topaz I, and the 3kW Buk reactor. However, there are no current active missions making use of a fission-based reactor. There are of course a number of space science missions (both spacecraft and surface rovers) making use of another form of nuclear power known as a Radioisotope Thermal Generator (RTG) that utilizes the radioisotope decay heat from a radioisotope such as plutonium that is used as a General Purpose Heat Source (GPHS) at the heart of a number of RTG designs. These RTG-class of nuclear power sources are quite useful for small robotic missions with modest power requirements measured in hundreds of watts; they are not, however, practical to be scaled much beyond the 1 kW power level. NASA does have a fission based reactor solicitation in work to request the development and implementation of a 10 kW Fission Surface Power (FSP) reactor to support the future human lunar exploration program Artemis as lunar nights are really long and really cold. This power category is still far short of the megawatt power levels necessary for a human-class NEP system[8]. The Department of Defense (DoD) has a form of nuclear propulsion being studied/developed with the project name DRACO. This class of nuclear propulsion is a nuclear thermal rocket which works by passing hydrogen gas through an extremely hot nuclear reactor and then allowing the super-heated hydrogen gas to escape and expand by means of a rocket nozzle. The appeal of this particular approach is that it offers high-thrust along with high-specific impulse in the 900 s performance range. Even so, there are significant engineering challenges to overcome and while the specific impulse is much higher than a chemical propulsion system, this unique form of nuclear (thermal) propulsion is still not sufficient to take humans to the outer solar system.

3 Fusion Propulsion

As mentioned in the video, in order to reduce interstellar transit times down from thousands of years to the ∼century timeframe, we need to move a bit into the unknown - at least from an engineering perspective - and engage the idea of fusion propulsion. At first blush, one might consider simply changing out the fission heat source of the previously discussed NEP architecture with a fusion heat source generating power by *burning* a plasma to fuse deuterium and tritium together to form helium, neutrons, and energy to generate heat power. Just as was done for NEP, the heat power could be used to drive a thermodynamic cycle to provide electric power + waste heat where the electric power is used to power the electric propulsion system resulting in a Fusion Electric Propulsion (FEP) architecture. However, it is much more likely that the fusion process will be used to directly generate thrust as the energy of the fusion products has the potential to yield a much higher specific impulse allowing for much higher cruise speeds than NEP or FEP. This type of approach is referred to in the literature as Direct Fusion Drive (DFD) where the fusion reaction directly drives the propulsive process - e.g. the propellant is simply the ash products of the fusion process directed out the back of a spacecraft by means of a magnetic nozzle.

The fusion spacecraft depicted in the video has two counter-rotating elements at the fore of a long central truss structure to provide artificial gravity for the human crew. The aft portion of the truss has some high temperature radiators, propellant tanks, and the fusion engine pod. The video quotes a transit time of ∼6 months to reach the orbit of Saturn, and a total transit time of 102 years to reach and capture at Proxima Centauri. The same environmental assumptions from the simple NEP model are used: gravity off; ignore planetary orbit speeds; radial trajectories. The model fusion spacecraft has a total mass m_0 of 8,000,000 kg and a final mass of m_f of 1,000,000 kg with a resultant mass ratio of 8. Just as was done for NEP, there is no staging and the spacecraft captures at Proxima Centauri. The specific impulse used for the fusion electric propulsion is 1,400,000 s[9] with an initial thrust to weight for the spacecraft of 0.001 resulting in an effective power level of 539 GW with 100% efficient electric propulsion. The total thrusting time for the spacecraft is 38.8 years with a portion of that time serving to accelerate the craft prior to interstellar cruise and the remaining balance of time to decelerate the craft for capture at Proxima Centauri. The peak velocity of the fusion spacecraft during interstellar cruise is 0.0476 c and a total mission Δv of 0.0952 c.

The reader may be wondering why is it that fusion propulsion yields such an improvement over the fission-based NEP architecture? First, it is a matter of energy density - the energy density of typical

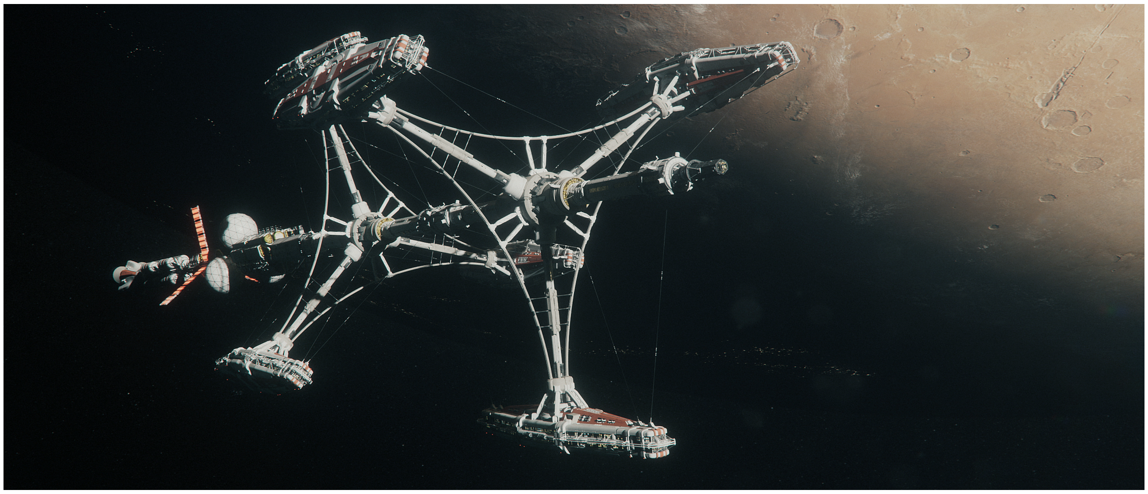


Figure 3: Enlarged view of the Fusion spacecraft with the two concentric spinning elements for artificial gravity. Propellant tanks and high temperature heat rejection can be seen towards the aft of the spacecraft with the direct fusion drive system at the very aft end of the ship.

nuclear fuels such as uranium is $\sim 80 \times 10^6$ MJ/kg while the energy density of deuterium-tritium fusion is $\sim 340 \times 10^6$ MJ/kg. But this is only the beginning of the advantage fusion has over nuclear - a fusion reactor is a plasma by definition and is therefore already in a state amenable to be utilized directly as an electric propulsion system if you will. A fusion reactor can use the fusion process to directly energize the "propellant" yielding an extremely high exhaust velocity of the fusion reaction products well exceeding the exhaust velocities possible in a traditional form of electric propulsion. Thus the advantage is two-fold: fusion systems will have higher overall power magnitudes and also be capable of specific impulse values that range from ten to one hundred times higher than a NEP equivalent architecture.

When might a fusion power/propulsion systems become a reality? In the interest of a crawl-walk-run mindset, a better way to pose the question is when might a terrestrial fusion power system become a reality? Fusion is often quipped to be the power source of the future with the punch line being that it always would be...in the future. But this pithy account of affairs is not really a fair reporting of the overall empirical progress towards the idea of achieving a breakeven fusion experiment in the lab. While there are numerous fusion approaches being explored with the goal of realizing a terrestrial fusion power plant, the one category with the most extensive and well documented empirical history is Magnetic Confinement Fusion (MCF) embodied in the form of a tokamak device. First conceived in 1968 by a team of soviet scientists, this category of fusion research has progressed quickly towards the goal of achieving net heat-energy out - e.g. more heat energy out than heat energy in with a peak performance of roughly 2/3 being achieved by the Japanese reactor JT-60(U) in the mid 1990's. These successes fed into the global plan to implement a terrestrial fusion demo plant capable of achieving a physics coefficient of performance of between 5 and 10 as embodied in the form of the international ITER fusion project [9] with a scale model depicted in Fig. 4. The ITER fusion demo plant is being assembled in southern France with first plasma set to occur no earlier than 2025 and deuterium-tritium operations to begin no earlier than 2035. But the international juggernaut ITER may get lapped by some smaller and more agile startups seeking to beat ITER to the punch. But how could something like this ever happen? As it so happens, the disruptive supporting technology that may have provided industry with the key ingredient necessary to facilitate a proverbial end-run to the fusion promised land whereby beating ITER is high temperature superconducting tape - specifically Rare-earth barium copper oxide (ReBCO) tape. ReBCO tape can manifest magnetic field magnitudes significantly higher than those possible in the 1990's, and much higher than the assumed 5 tesla magnetic field capability of the ITER. In September of 2021, Commonwealth Fusion, an MIT commercial spinoff company, achieved a magnetic field magnitude of 20 tesla in a representative toroidal field coil pack[10] for their SPARC demonstration reactor. The benefit of such larger magnetic field levels is the ability to shrink the tokamak reactor volume by a factor of 100 putting demo-plant efforts back into the realm of commercial startup and universities. A number of MCF contenders

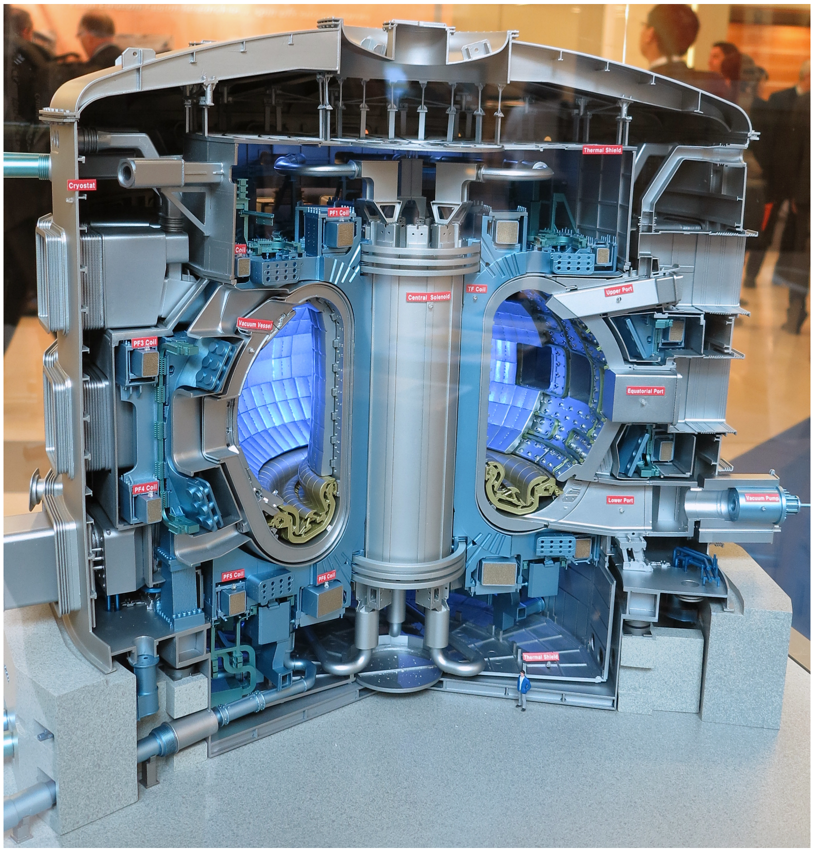


Figure 4: Scale model of ITER reactor with human at bottom center for relative scale - photo credit: Conleth Brady/IAEA, CC BY-SA 2.0

are working towards a fusion demonstration plant with a physics coefficient of performance in the 5-10 range by the 2025 time frame. In addition to the MCF teams racing to implement terrestrial fusion power demonstration devices, there are a number of other teams working on alternate fusion schemes, and three noteworthy approaches are highlighted here:

- General Fusion is a Magnetized Target Fusion (MTF) approach that injects a compact toroid of magnetized plasma into a cylinder of spinning liquid metal that is mechanically compressed to trigger fusion reactions in the magnetized plasma.
- TAE Technologies uses a Field-Reversed Configuration (FRC) with neutral beam injections to stabilize the plasma and achieve higher temperatures for longer durations (TAE also hopes to use the proton + boron-11 fuel cycle where the fusion products are all charged particles).
- Helion Energy uses a pulsed Magneto-Inertial Fusion (MIF) approach colliding two plasmoids in a central chamber to generate an FRC state, compressing the plasma to fusion conditions, and allowing it to expand to generate power..

We will close the fusion section by noting that the dark horse for near-term fusion propulsion might be a hybrid approach where the fusion rocket still requires power from the spacecraft to operate. But wait, isn't this counter to the whole value proposition of fusion propulsion - how is this useful? Hear out the argument - if one were to implement a fusion propulsion system that had a physics coefficient of performance of say 3, this is not likely high enough to drive a thermodynamic power conversion process to provide net power for the spacecraft and run the fusion reaction. However, if an architecture were to say couple a nuclear reactor to the fusion rocket, the nuclear reactor could provide power to the fusion rocket, which would then engage the fusion reaction process to add additional thermal power to the propellant plasma based on the physics coefficient of performance. This has the net effect of increasing the effective jet power that can be achieved with a NEP system. Said another way, the NEP spacecraft gets a higher thrust to power while still maintaining high specific impulse performance. This fusion rocket concept is currently being explored by Helicity Space.

One last item to highlight before shifting to *Breakthrough*, fusion is an interstellar-enabling category of propulsion technology that can achieve cruise velocities that fall within the 5% to perhaps even high as 10% of the speed of light. Is there another approach that can achieve higher cruise velocities for human-crewed spacecraft architectures? The only thing within the context of known physics that can achieve higher cruise velocities for large payload would be matter-antimatter propulsion. Matter-antimatter propulsion utilizes the matter-antimatter annihilation process to generate highly energetic particles traveling at speeds very near the speed of light, thus yielding very high specific impulse values. This highly efficient conversion of propellant to kinetic energy allows a spacecraft equipped with this type of propulsion system to attain cruise velocities that may just exceed 20% of the speed of light. However, there are not commercial entities that produce anti-matter in bulk and the cost per kg of antimatter as of this writing is in excess of $60 trillion a gram - never mind the containment challenges as if antimatter comes into contact with matter, it by definition annihilates in nature's most energetic way.

4 Breakthrough Propulsion

The final vignette of the short film is the segment dealing with breakthrough category of propulsion. The particular propulsion technique highlighted is the idea of a space warp. The same mathematics (general relativity) that establishes the ultimate cosmic speed limit (speed of light), also allows for two loop holes to facilite hyper-fast travel such that one can travel to another star system in days/weeks/months as measured by clocks on board the spacecraft which are in sync with clocks in mission control - space warps and wormholes. The video depicts a space warp capable spacecraft complete with two engine nacelles that would need to generate a specified amount of exotic matter or negative vacuum energy density. Spacetime would respond in such a way that space would contract in front of a spacecraft and expand behind the spacecraft. As space can expand and contract at any speed, there is no longer a cosmic speed limit preventing hyper-fast travel to another starsystem in months or even less. Figure 5 depicts the York time for the Alcubierre warp metric [11] where the York time can be thought of as a three dimensional strain on space - e.g. cubic meters per cubic meter. There is a toy spacecraft overlayed on top of the plot which consists of a ring wrapped around a cylindrical shape. The ring represents the system that manifests the negative vacuum energy density necessary to form the warp bubble while the cylindrical section represents the section where the crew or sensitive scientific equipment would be located.

The spacecraft in the video, shown here in Fig. 6, is assumed to be capable of achieving an effective speed of 10 times the speed of light, or 10c if you will. There is no acceleration time as the idea of a space warp is such that it turns on and off with the proper acceleration α being formally zero, so a zero-g state of affairs. The transit time from Mars to Saturn is 6.7 minutes and the transit time to capture at Proxima Centauri is 5.2 months. The assumed effective speed of 10c is not necessary an upper limit on the idea of a space warp and the effective speed could just as well have been assumed to be 50c or 100c. It should also be noted that effective space warp velocities below 1c may still be of significant interest. Recall that the transit speed for the fusion propulsion system was stated to be a peak cruise velocity of 0.05c. What if one could achieve 0.5c? While this would result in transit times measured in years, it is still a significant improvement on the transit time for the fusion propulsion system.

How viable is the idea of a spacedrive, a spacewarp, or a wormhole? If we envision our current understanding of physics as it stands today as a Venn diagram, there would be two circles side by side touching at a single point. One circle would have the words *quantum mechanics* in it representing our current understanding of how the microscopic world of sub-atomic particles behave. The other circle would have the words *general relativity* in it representing our understanding of how the macroscopic world works such as how galaxies evolve and the cosmos expands. Just this knowledge of the natural world affects our lives everyday - consider the scenario where you use your phone to navigate to see a friend at a new restaurant. The solid-state technology in the phone is only possible through our understanding of the microscopic world by means of quantum mechanics. The GPS technology comprised of the GPS chip in the phone talking to the GPS satellites is only as precise as it is because we make software corrections for special relativistic time-dilation effects (orbital velocity) and general relativistic time-dilation effects (orbital altitude) on the hyper-precise atomic clocks on-board the

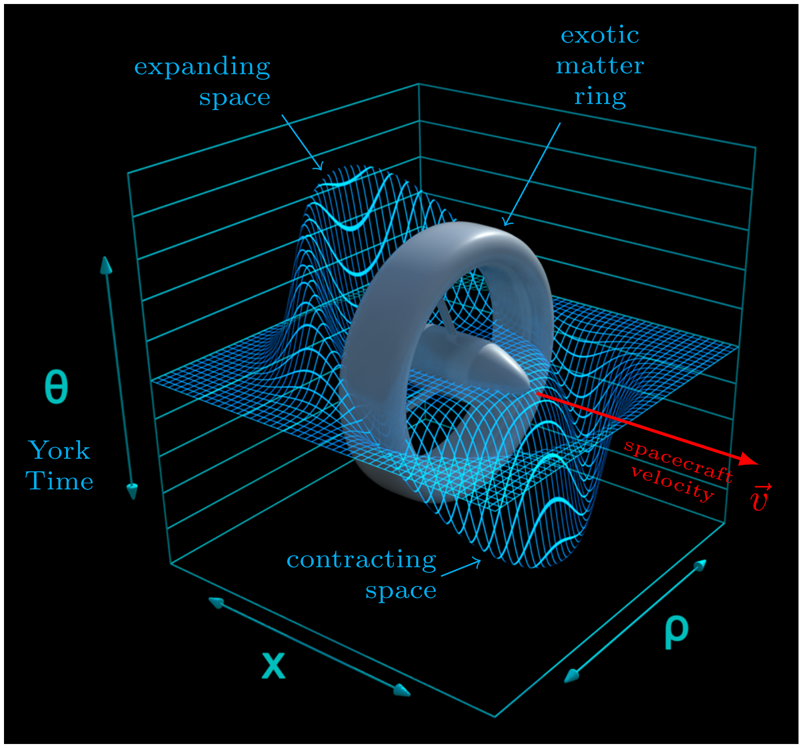


Figure 5: The figure shows a plot of the York time for the Alcubierre metric. The York time represents expansion and contraction of space associated. Overlayed over the plot is a simple representation of a spacecraft illustrating the alignment of the exotic matter ring with the York time.

GPS-halo of satellites. But the two circles on the Venn diagram do not overlap suggesting to us that there must be a larger circle than encapsulates both existing circles and representative of a more generalized understanding of the world such that there in a mathematical framework that successfully models both the microscopic and macroscopic worlds. This frontier of physics is likely the key area where new understandings of physics may equip us with insights that help us impement some of the disruptive technologies mentioned earlier such as a spacedrive, spacewarp, or a wormhole. We know spacewarps and wormholes are mathematically possible, but we do not currently know what to "build" to make one manifest - perhaps the development of physics foundations will enable us to reduces these enabling ideas to practice.

Consider that Einstein derived his famous equation $E = mc^2$ in 1905 showing for the first time the relationship between matter and energy. In 1932 Cockcroft and Walton split the atom for the first time in a laboratory experiment where the team bombarded beryllium and lithium targets with $\sim$ 600 keV protons to split the atoms and generate alpha particles (helium-4 nuclei). In 1942 under a squash court at the University of Chicago, the world's first nuclear reactor called the Chicago Pile-1 was turned on and generated a whopping 0.5 watts. On July 6, 1945, the United states detonated the worlds first nuclear weapon in the Trinity nuclear test conducted in the Jornada del Muerto desert in New Mexico. History shows us that it took just 40 years from the inception of a disruptive understanding of the natural world to the manifestation of one of the most energetic processes known to humanity - and all these "firsts" without the advent of computers. Imagine how much faster the development of an idea to a technological application might be when driven by a world-wide network of scientists equipped with computational capability only dreamt of just half a century ago - exponential growth of capability.

5 Discussion

This short engineering note is meant to be a companion to the short film titled "Go Incredibly Fast" and provide some of the simple model details used to arrive at the transit time numbers quoted in the

Figure 6: The figure depicts a still from the short film that depicts a warp capable ship. The ship includes two "warp rings" that would contain the required amount of negative vacuum energy density to achieve an effective velocity of 10c.

video. One of the unique challenges of concise communication on an inherently technical subject is to balance the desire to *tell everything you know* with the other extreme of potentially being superficial when reporting on a technical matter - be brief but not superficial if you will. As an illustration, when a technical team is reporting to management stakeholders on critical technical matters needing timely decisions, it is essential for the technical team representatives to concisely summarize the matter, identify options to be traded, and provide specific recommendations for disposition. Management stakeholders responsible for the implementation and operation of complicated engineering systems such as those connected with human spaceflight are routinely saturated with technical information thus resulting in limited bandwidth to accommodate ancillary and non-critical information. With this boundary constraint in mind, the supporting technical teams owe it to themselves, the broader team, management, and the overall success of the endeavor to strive to be brief but not superficial when reporting out on critical issues to leadership. This can be done and done effectively, it just takes practice and the discipline to resist the urge to report on every detail, every supporting thought process, details of elements traded out, engineering calculation assumptions, anecdotal experiences, etc. When done effectively, an organization runs efficiently, is tough and competent, and makes constant measured progress toward achieving the pinnacle objective of the organization.

Epilogue

As mentioned at the outset, the objective of this inspirational-educational short film is to communicate the essence of the time-distance problem of deep space exploration and highlight some possible propulsion approaches one might utilize to cross the vast distances between the stars. Neither the film nor this article are meant to be comprehensive, and references have been provided for the curious to investigate a number of the other approaches developed in the literature such as solar sails, beamed energy propulsion, and anti-matter propulsion. One unique approach worth highlighting here is a robotic light-driven-sail mission to Proxima Centauri called Project Starshot[12] which is being developed by our sister organization, Breakthrough Initiatives (see Fig. 7 for an artistic impression of the light-driven sail). The starshot approach in short, is to utilize a large, ground-based phased-array of lasers with a combined power output in the 100 GW range to accelerate a ~ 5 m diameter sail to 20% of the speed of light thus allowing for a 20 year transit to Proxima Centauri. This interstellar sail spacecraft would do a flyby of the Proxima Centauri system collecting scientific data, and perhaps directly imaging some of the exoplanets such as Proxima Centauri b which resides in the habitable zone. While this noted approach has a number of non-trivial engineering challenges, all of the underlying system concepts are based on known physics. Even though LSI's primary vision is to enable human exploration of the stars, LSI supports the development of these smaller interstellar robotic probe concepts as they may very well be the precursor robotic sentinels to an eventual human-crewed mission.

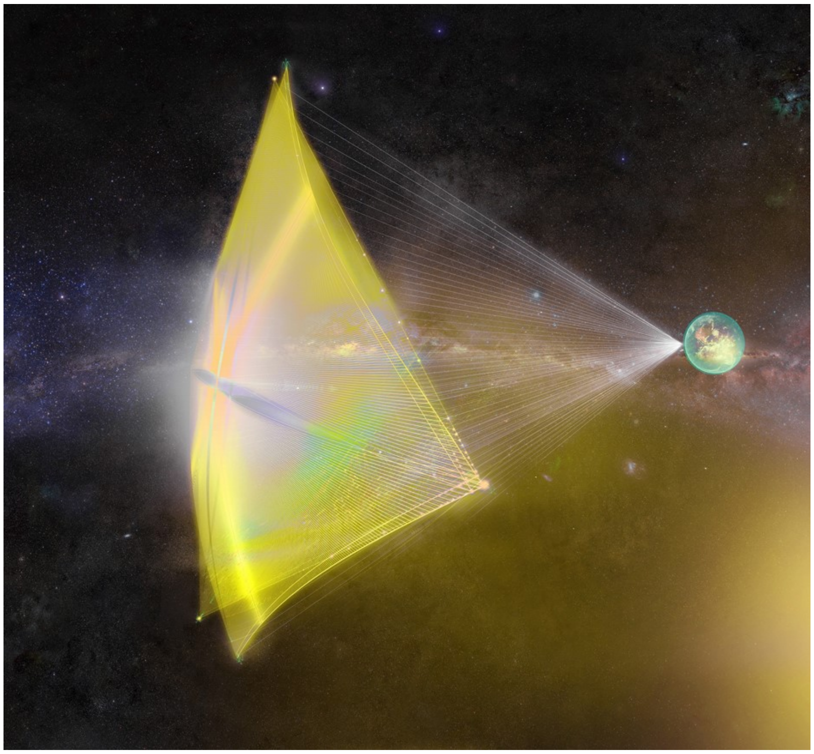


Figure 7: The figure depicts an image of a light driven sail being accelerated up to 20 % of the speed of light so that it can reach Proxima Centauri in 20 years. Credit Breakthrough Initiatives, used with permission.

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Notes

[1] video is available at: https://youtu.be/RiJFo-kaJBQ, directed by Erik Wernquist, written by Erik Wernquist and Harold White, released April 25, 2022

[2] The sun is a fusion reactor after all - a really big one at that.

[3] The Iron Man ARC fusion power source the size of a coffee cup is not currently available to mission planners.

[4] such as uranium-235 (U-235)

[5] This specific impulse is only a slight increase in performance over an envisioned 50,000 s, 50-kW gridded ion thruster processing lithium propellant[13].

[6] "that's no moon, it's a space station!" - Ben Kenobi, Star Wars, Episode IV

[7] As of 2022 - the DoD uses approximately 30 terawatt-hours of electricity per year and more than 10 million gallons of fuel per day[8]

[8] your garden variety locomotive has an electric power budget that fall within the 2-6 MW range

[9] For comparison, the specific impulse assumed for Project Icarus Inertial Confinement Fusion (ICF) is 1,000,000 s. The 1,400,000 s assumption is still well below the speculated theoretical limit of ICF performance. If it is not achievable, then a higher mass ratio would be necessary to achieve the mission Δv.