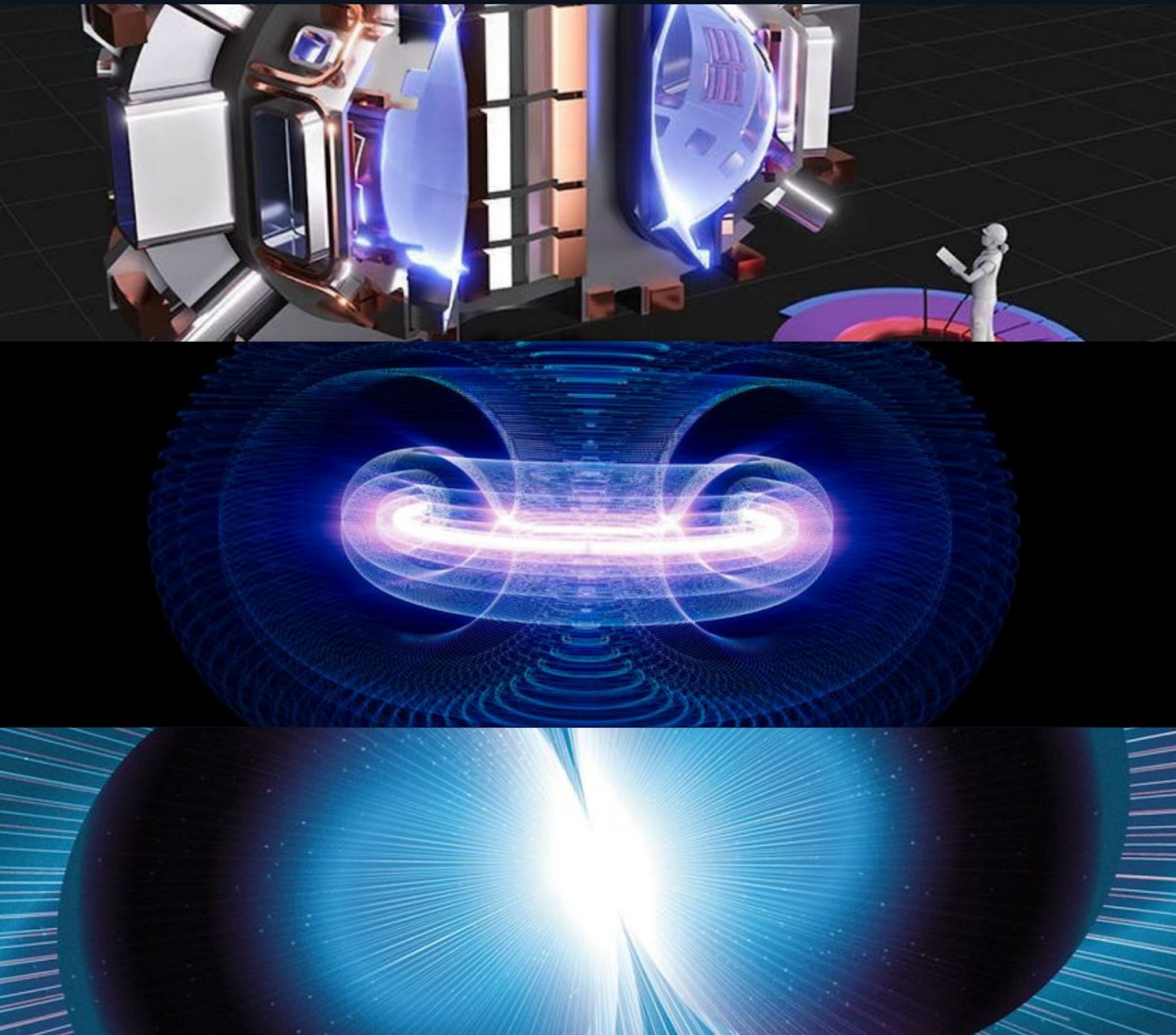
THE ECONOMICS OF FUSION ENERGY:
ASSESSING THE COMMERCIAL VIABILITY OF COMMONWEALTH FUSION SYSTEMS' ARC DEVICE



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DECEMBER 2020

Summary

This paper assesses the commercial viability of the Affordable, Robust, Compact (ARC) fusion reactor under development by Commonwealth Fusion Systems (CFS) via the scaled-down, experimental SPARC reactor. The assessment begins with an analysis of CFS' history, investors, and goals. ARC's innovative design is then evaluated using some notable critiques on the commercial and technological viability of fusion reactors as a guide on the necessary challenges to overcome. To provide situational awareness, the paper investigates other firms pursuing fusion. Indirect competitors in the broader renewable space are also analyzed to distill a necessary Levelized Cost of Energy (LCOE) that ARC must achieve to be competitive in the energy market of the 2030s and beyond. Combining the technological assessment with an understanding of the scalability factors that face ARC, **the paper arrives at the conclusion that although CFS will likely achieve net positive energy production with the SPARC reactor by 2030, it is unlikely that ARC fusion reactors will be commercially viable before 2040.**

"Many people in fusion get down from time to time because of the big problems they face, but the benefits are so huge that it is irresponsible not to try."

-Dr. Scott Hsu, ARPA-E Fusion Energy Program Director[1]

Introduction

Nuclear fusion is a natural process which powers stellar cores by fusing the atomic nuclei of lighter elements into heavier ones, releasing massive amounts of thermal energy in the process. With the exception of antimatter-matter interactions, fusion is the most energy dense physical interaction known to humanity.[2] There are many types of fusion reactions, stellar cores can fuse every element up to iron before they collapse, but the most useful variants typically involve lighter atomic nuclei like hydrogen and helium. The most common type of fusion in nuclear fusion reactors, and one that will be investigated thoroughly in this paper, is the fusion of deuterium and tritium, two isotopes of hydrogen.[3] However, other possible fusion reactions include the use of helium-3 and boron-11.[4]

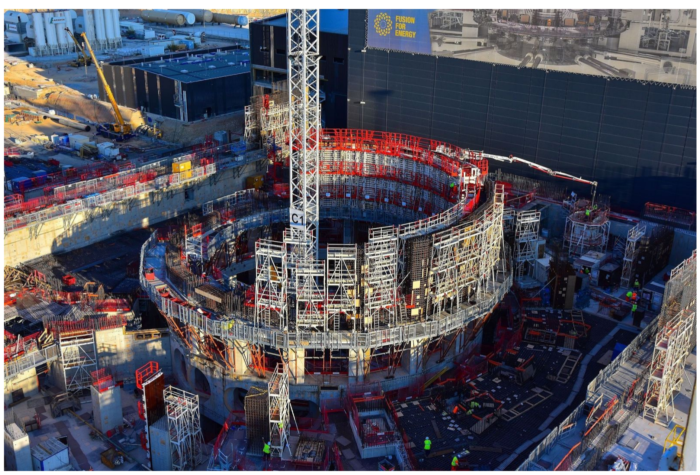
Fusion energy promises to supply large volumes of clean, virtually inexhaustible power and has been a dream of scientists and technologists since it was first hypothesized in the 1930s.[5] Many successful fusion reactors of varying designs have been built over the past 60 years, but as of 2020, none have been able to produce more energy than what is required to start and sustain the reaction.[6] The closest reactor to breaking this net energy balance (Q) was the Joint European Torus which achieved Q = 0.7 in 1997.[7] Due to the immense difficulties involved with overcoming Q, nuclear fusion reactors have largely been relegated to research.[8] However, this is about to change.

A wave of private investment and government programs are bringing the promise of practical fusion energy closer than ever before. It is a running joke in scientific and energy circles that fusion power is always 30 years away; there is a large amount of skepticism surrounding fusion for this reason. Put simply, fusion is hard. There are many challenges left to overcome before it is a reality. However, the technological, financial, and political stars are aligning to produce a good chance, the best in history, that Q>1 will be broken inside this decade and that commercial fusion power will follow roughly a decade after that. This paper investigates

[1] Thomas, Harry. "Interview with Dr. Scott Hsu." 20 Nov. 2020.
[2] An Energy Technology Distillatefrom the Andlinger Center for Energy and the Environment at Princeton University, Fusion Energy via Magnetic Confinement.
[3] Ibid.
[4] Ibid.
[5] Ibid.
[6] Ibid.
[7] Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.
[8] An Energy Technology Distillatefrom the Andlinger Center for Energy and the Environment at Princeton University, Fusion Energy via Magnetic Confinement.

a private firm's lean, ambitious plan to achieve just that, but it would be remiss not to mention the largest effort underway to finally crack fusion.

The International Thermonuclear Experimental Reactor (ITER) is both the largest science experiment and largest international megaproject in history.[9] Currently under construction in the South of France, ITER is a massive deuterium-tritium (D-T) tokamak reactor which relies on magnetic confinement, the process of superheating gas into plasma and controlling it with incredibly powerful magnetic fields to kickstart a fusion reaction,[10] to produce a projected 500 MW of thermal fusion power and break Q by a factor of 10.[11] The experiment is a collaboration between 33 nations and will cost roughly $22 billion,[12] but some cost estimates have shown that figure to balloon in the future to over $60 billion.[13] ITER provides useful context when contrasted with the private approach described in this paper, which uses the exact same D-T tokamak design. Although ITER is likely to succeed, it has caught a lot of skepticism and criticism for its lumbering, excessively bureaucratic approach.[14] Calling the most expensive science experiment in human history, a partnership between 33 different nations with varying languages and institutions, excessively bureaucratic is honestly an understatement. That being said, the stage is set. As private, domestic, and international efforts race to be the first to break Q, the promise of fusion energy has never been brighter.



:The 400 meter foundation of ITER under construction in Provence, France.[15]

[9] Jassby, Daniel. "Fusion Reactors: Not What They're Cracked up to Be." *Bulletin of the Atomic Scientists*, 24 Aug. 2020, thebulletin.org/2017/04/fusion-reactors-not-what-theyre-cracked-up-to-be/.
[10] An Energy Technology Distillatefrom the Andlinger Center for Energy and the Environment at Princeton University, Fusion Energy via Magnetic Confinement.
[11] Jassby, Daniel. "Fusion Reactors: Not What They're Cracked up to Be." *Bulletin of the Atomic Scientists*, 24 Aug. 2020, thebulletin.org/2017/04/fusion-reactors-not-what-theyre-cracked-up-to-be/.
[12] "ITER Members." *ITER*, www.iter.org/proj/Countries.
[13] Ibid.
[14] Ibid.
[15] "Vacuum Vessel." *ITER*, www.iter.org/mach/vacuumvessel.

Commonwealth Fusion Systems

Commonwealth Fusion Systems (CFS) is a startup based in Cambridge, Massachusetts and established in 2018 with the goal of commercializing fusion power. Its story began in 2014 when MIT's Plasma Science and Fusion Center (PSFC) outlined a detailed approach to build a fusion reactor that could in theory produce grid-scale energy.[16] The design, known as the Affordable, Robust, Compact (ARC) tokamak reactor inspired CEO Bob Mumgaard, who was doing postdoctoral research at MIT PSFC at the time, to start CFS in 2018 with the goal of bringing the idea into reality.[17] CFS works closely with MIT PSFC in its efforts to build the reactor, and a large portion of CFS' leadership are alumni of the PSFC.[18]

Since 2018, CFS has held two series A funding rounds that yielded a total of $199 million from over 16 investors: a remarkably large initial investment yield for a new startup.[19] Breakthrough Energy Ventures, the next generation energy fund backed by billionaires Bill Gates, Jeff Bezos, Jack Ma, and Richard Branson,[20] and Temasek Holdings, a Singaporean private equity firm that focuses on sustainable, long term returns,[21] are the two largest investors in CFS.[22] Other notable investors include Chris Sacca's Lowercase Capital, the major Silicon Valley venture capital firm Khosla Ventures, and the Italian petroleum giant ENI.[23] The amount of funding CFS has received from notably inscrutable and illustrious sources is a testament to the feasibility of its plan and quality of its MIT PSFC derived talent.

CFS has an aggressive timeline to meet its objective of commercializing fusion energy. SPARC, the "Kittyhawk of Fusion", is an experimental tokamak reactor that will precede ARC and is planned to break Q for the first time in history by a factor of 2 when it is completed in 2025.[24] It will be built in collaboration with MIT PSFC as a research and proof of concept reactor that will stay with MIT after it tests the components necessary to build ARC. The ARC and SPARC designs are built around new high temperature superconductors developed by MIT PSFC that allow for much higher field strengths than older tokamak designs.[25] CFS plans to apply the lessons learned on SPARC to ARC and hopefully have a functioning ARC fusion plant supplying grid-scale energy by 2033.[26]

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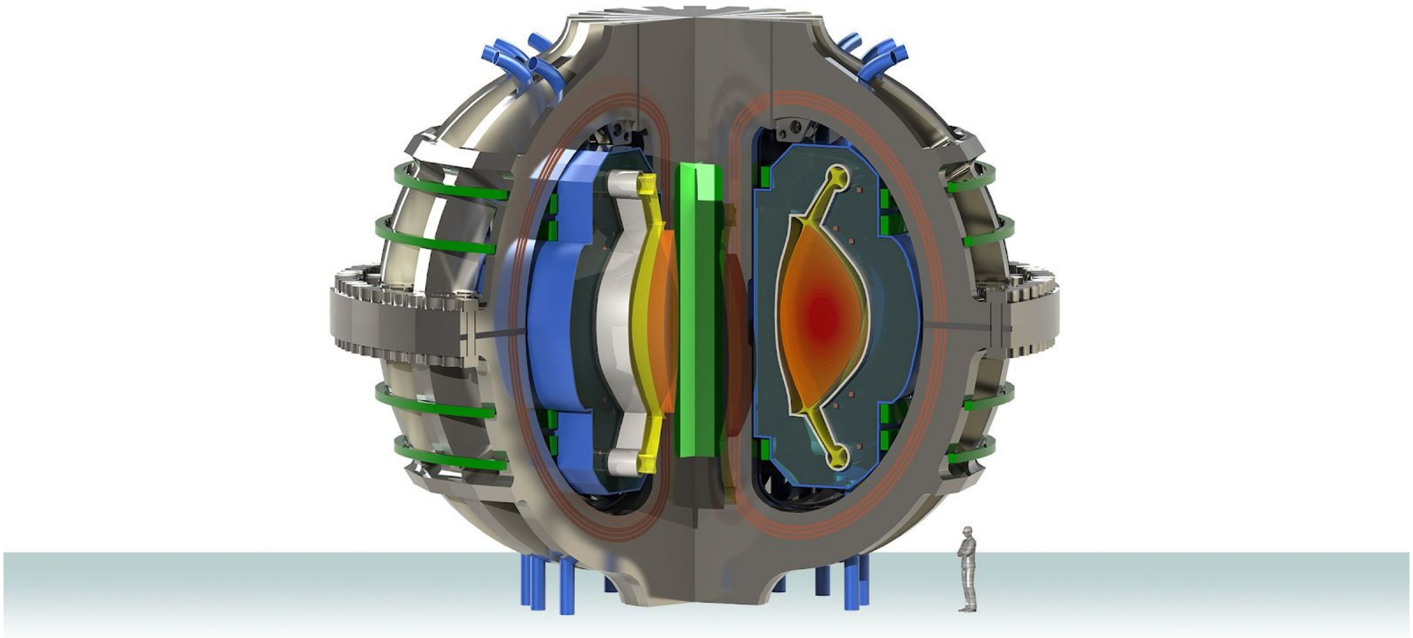
[16] Fountain, Henry. "Compact Nuclear Fusion Reactor Is 'Very Likely to Work,' Studies Suggest." *The New York Times*, The New York Times, 29 Sept. 2020, www.nytimes.com/2020/09/29/climate/nuclear-fusion-reactor.html.
[17] Ibid.
[18] Ibid.
[19] "Commonwealth Fusion - Crunchbase Company Profile & Funding." *Crunchbase*, www.crunchbase.com/organization/commonwealth-fusion-systems.
[20] "Commonwealth Fusion - Funding, Financials, Valuation & Investors." *Crunchbase*, www.crunchbase.com/organization/commonwealth-fusion-systems/company_financials.
[21] Ibid.
[22] Ibid.
[23] Ibid.
[24] Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.
[25] Ibid.
[26] Ibid.



: ARC reactor concept.[27]

The ARC Reactor

The ARC reactor is a scaled up version of SPARC and Commonwealth Fusion's plan to commercialize fusion energy.[28] It's component technologies and design were first described and hypothesized by MIT PSFC as a way to break Q with the smallest possible reactor in 2014. ARC is a magnetic confinement Tokamak that utilizes the deuterium-tritium (D-T) fusion process to power a conventional steam cycle to generate energy.[29] More research and investment has gone towards magnetic confinement D-T Tokamaks than any other type of fusion: mainly because D-T fusion requires the least amount of energy to start a reaction process.[30] The ARC reactor builds off this stable understanding by implementing a host of innovative solutions to increase efficiency and potentially reach Q = 13.6 to supply over 200 MW of electricity.[31]

The complexity of fusion reactors is dizzying. Every process and component has an impact on the holistic design that generates a web of problems that must be solved by other

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27 Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.
28 Ibid.
29 Ibid.
30 "Nuclear Fusion Power." *Nuclear Fusion : WNA - World Nuclear Association*, 2020, www.world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.aspx.
31 Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.

processes and components; feedback loops, both virtuous and vicious, are innate and seemingly infinite in fusion.[32] Many researchers are pessimistic about the potential for commercially viable fusion because of these problems. The main critiques of fusion energy can be distilled down to issues with size, electricity consumption, tritium fuel losses, and neutron activation.[33] ARC's design overcomes many of these problems through a variety of innovative technologies and processes.

Reactor Size

One of the prevailing theories in fusion research is that in order to achieve higher levels of efficiency, reactors need to be scaled up to incredibly large sizes. ITER is planned to have a fusion vacuum vessel that measures 19.4 meters across.[34] This enormous size has led to much skepticism about the potential for commercial fusion power generation due to the massive construction and maintenance costs associated with such a large form factor. Commercial fission reactors are frequently unprofitable without government subsidies and tax credits for this reason today.[35] ARC is planned to be about half the size of ITER while producing the same amount of thermal energy, and the technology driving this reduction in size is the higher magnetic field strength enabled by the keystone of ARC's design and CFS' current focus: High Temperature Superconductors.[36]

ARC relies on new rare-earth barium copper oxide (ReBCO) high-temperature superconducting (HTS) tapes to achieve much higher internal magnetic field strengths than traditional tokamaks.[37] One of the main issues with fusion reactor designs that lead to the need to scale up to incredible sizes was the fact that low temperature superconductors need to be kept at extremely cold temperatures and were limited in the magnetic field strengths they could produce. Theoretical fusion power density is proportional to the fourth power of the magnetic field intensity inside a reactor; increases in magnetic field strength will bring outsized increases in fusion power density.[38] ARC will use ReBCO HTS ribbon shaped tapes that will not require the complicated coolant systems used for low temperature superconductors to produce an unprecedentedly strong magnetic field.[39]

As important as the increase in fusion power density provided by the HTS tapes is, another set of benefits to consider are those provided by their small form factor. Not only will the small size of the tapes significantly reduce the size of the reactor compared to large traditional

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[32] Thomas, Harry. "Interview with Dr. Scott Hsu." 20 Nov. 2020.

[33] Jassby, Daniel. "Fusion Reactors: Not What They're Cracked up to Be." *Bulletin of the Atomic Scientists*, 24 Aug. 2020, thebulletin.org/2017/04/fusion-reactors-not-what-theyre-cracked-up-to-be/.

[34] "Vacuum Vessel." *ITER*, www.iter.org/mach/vacuumvessel.

[35] Thomas, Harry. "Interview with Dr. Scott Hsu." 20 Nov. 2020.

[36] Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.

[37] Ibid.

[38] "Fusion Power." *Fusion Power - an Overview | ScienceDirect Topics*, www.sciencedirect.com/topics/engineering/fusion-power.

[39] Thomas, Harry. "Interview with Dr. Scott Hsu." 20 Nov. 2020.

superconductors, they will also be demountable and swappable, allowing for modularity that will be important later.[40]

Recirculating Power

The term *recirculating power* in fusion reactors refers to the amount of power produced in the reaction that must be diverted to heat and control the plasma. This is widely regarded as a major problem for fusion, and much emphasis has been placed on reducing recirculating power requirements.[41] The massive power draw from the systems that heat and control plasma in traditional reactor designs like ITER eat up a bulk of the produced energy and significantly lower the efficiency of the plant, reducing any hope of breaking Q and economic competitiveness.[42] ARC overcomes many of the issues associated with recirculating power by reducing power consumption in the coolant pumping and heating and current drive systems.

As opposed to ITER which uses water as coolant, ARC plans to use a fluorine lithium beryllium molten salt blanket that provides much greater thermal inertia than water coolant systems. One potential approach that ARC may use to reduce recirculating power requirements is to operate the reactor in a pulsed mode where the thermal inertia from the molten salt blanket smoothes out power flows.[43] However, this pulsed mode will not be as effective for long term power generation as operating the reactor in a steady-state where the plasma is stable for longer periods of time.[44]

ARC might opt to use a Lower-Hybrid Current Drive (LHCD) system which is theorized to significantly improve efficiency when used in conjunction with the high magnetic fields provided by the HTS tapes.[45] Opting for this method will allow the reactor to control plasmas at high Q in steady-state, which would notably increase the reactor's efficiency. Unfortunately, no physical testing on LHCD systems in high field environments has been done, but computer modeling by CFS and MIT PSFC suggests that, "25% of the current could be driven with only 5% of the total power."[46] The steps forward to developing the systems that will enable efficient reactor power flows and diminish recirculating power are still somewhat vague, but this aspect of ARC makes it apparent that the novel, enabling component of the design as a whole are the HTS tapes. Many essential processes hinge on the magnets' ability to produce high field strengths in the reactor core.

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40 Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.

41 Jassby, Daniel. "Fusion Reactors: Not What They're Cracked up to Be." *Bulletin of the Atomic Scientists*, 24 Aug. 2020, thebulletin.org/2017/04/fusion-reactors-not-what-theyre-cracked-up-to-be/.

42 Ibid.

43 Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.

44 Brans, Pat. "Science: New Steady State Analysis." *ITER*, 24 Feb. 1970, www.iter.org/newsline/-/3401.

45 Molavi-Choobini, Ali Asghar, et al. "Study of Lower Hybrid Current Drive for the Demonstration Reactor." *Nuclear Engineering and Technology*, Elsevier, 26 Feb. 2016, www.sciencedirect.com/science/article/pii/S1738573316000632.

46 Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.

Tritium Fuel Losses

Tritium is a radioactive isotope of hydrogen that has a nasty habit of diffusing through solid metal walls. D-T reactors fuse tritium with its lighter, nonradioactive sibling isotope deuterium.[47] Deuterium is relatively abundant in seawater, but tritium can not be found in large quantities on Earth and must be synthesized in nuclear fission or fusion reactors via interactions between high energy neutrons and lithium, making it expensive to procure.[48]

In an attempt to limit the amount of tritium that has to come from an exogenous source after initial ignition, fusion reactors contain some sort of lithium containing material near the core to create tritium and recycle it back into the fusion process. However, tritium's small atomic size allows trace amounts of the radioactive isotope to escape the containment vessel.[49] If these tritium losses are not contained, eventually the plant will run out of tritium and be forced to buy it from an expensive source. Not only is this economically untenable, it poses a public health risk because tritium can leach into the groundwater surrounding a fusion facility.[50]

ARC has an elegant yet vague solution to overcome tritium losses. The fluorine lithium beryllium molten salt blanket that the fusion containment vessel sits in limits tritium losses and allows for more efficient tritium breeding. However it is not clear to what degree it does so. Most tokamaks contain their tritium breeding material in a complicated series of pipe flows behind the main reactor wall.[51] In theory, ARC's continuous molten salt blanket will cover a larger portion of the reactor, limiting tritium diffusion through the containment vessel walls while simultaneously exposing more neutrons generated by the fusion plasma to more lithium in the blanket because a greater surface area is exposed to neutron flux than reactors that utilize pipe systems.[52] That being said, CFS is not clear in any of its published material to what extent the molten salt bath will reduce tritium losses. In the coming years, SPARC will test this approach and hopefully prove its viability.

Neutron Activation

The fusion of one deuterium atom and one tritium atom yields energy, one helium atom, and one high energy neutron (3-H + 2-H = 4-He + n (high energy)).[53] These neutrons are beneficial in the tritium breeding process described earlier, but pose a major problem for a fusion reactor. Neutron radiation *activates* material, meaning that it can make stable materials radioactive. When the neutrons generated by a fusion plasma interact with the components exposed to the inside of a reactor vessel and even some shielded by the reactor wall, *high energy neutrons are the most penetrative form of radiation,*[54] that material can become low-level nuclear

47 "Nuclear Fusion Power." *Nuclear Fusion : WNA - World Nuclear Association*, 2020, www.world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.aspx.
48 Ibid.
49 Jassby, Daniel. "Fusion Reactors: Not What They're Cracked up to Be." *Bulletin of the Atomic Scientists*, 24 Aug. 2020, thebulletin.org/2017/04/fusion-reactors-not-what-theyre-cracked-up-to-be/.
50 Ibid.
51 Thomas, Harry. "Interview with Dr. Scott Hsu." 20 Nov. 2020.
52 Ibid.
53 "Nuclear Fusion Power." *Nuclear Fusion : WNA - World Nuclear Association*, 2020, www.world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.aspx.
54 Ibid.

waste over time.[55] Certain materials are more prone to activation than others, but eventually, everything exposed to neutron irradiation will have to be replaced in a fusion reactor.[56] Aside from the ReBCO HTS magnets, the way that ARC overcomes neutron activation is one of the crowning achievements of its design.

Everything exposed to neutron flux in ARC is designed to be demountable and replaceable. The most notable aspect of ARC's modularity is its ease of access. Molten salt baths intuitively present a problem for modularity because they make it nearly impossible to access internal components in the reactor core that sit in front of the bath. Aside from covering a large surface area in the reactor vessel and thus preventing a large portion of the neutron activation that would occur in a more traditional fusion reactor, ARC's molten salt blanket is designed to be drainable so the reactor core is accessible via vertical lift.[57] This opens up a host of opportunities for component upgrades, replacement, and the disposal of neutron activated materials.

When neutron erosion eventually degrades the vacuum vessel and the magnets into low level nuclear waste, they will be safely removed and disposed of at a nuclear waste disposal facility. Removing and replacing activated material takes months in a scientific fusion reactor, with ARC it will take days.[58] This opens the door to iterative improvement of ARC as a whole as each component can be replaced, leading to compounding gains in efficiency and performance in the future. Moreover, SPARC will take advantage of modularity for the rapid, iterative development of the component technologies required for ARC.[59]

Innovation Required

All of the technologies planned for ARC are currently in development to be tested on SPARC and are highly subject to change. Innovation and incremental technological/process improvements are needed to fully realize ARC's design, but CFS has a detailed plan, scientific backing, and support from the highly accredited MIT PSFC. There are undoubtedly many more difficulties to designing the first commercial fusion reactor than are mentioned here that will make development exceptionally challenging. That being said, the progress that CFS has made with HTS and the financial support they have received from notable sources is a promising indicator that ARC's design and CFS' approach will work.

Direct Competitors

Commonwealth Fusion Systems, founded in 2018, is a newcomer in a diverse fusion startup scene that leverages a variety of approaches. Some of the leading firms in the space have been working for the better part of 20 years to make fusion energy a reality. Two of CFS' direct competitors are described below to provide some situational awareness in the budding fusion industry.

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55 Jassby, Daniel. "Fusion Reactors: Not What They're Cracked up to Be." *Bulletin of the Atomic Scientists*, 24 Aug. 2020, thebulletin.org/2017/04/fusion-reactors-not-what-theyre-cracked-up-to-be/.

56 Thomas, Harry. "Interview with Dr. Scott Hsu." 20 Nov. 2020.

57 Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.

58 Thomas, Harry. "Interview with Dr. Scott Hsu." 20 Nov. 2020.

59 Ibid.

TAE Technologies is a 22 year old company based in California focusing on developing a novel type of magnetic confinement fusion called Field Reversed Configuration (FRC) proton-boron 11 (H-B11) aneutronic fusion,[60] where no neutrons are emitted and alpha particles, helium nuclei, are the only products of the reaction.[61] H-B11 fusion is widely regarded as the holy grail of both fusion and energy as a whole due to its unparalleled energy density by mass and lack of neutron radiation. However, H-B11 fusion requires temperatures that are around 20 to 50 times higher than D-T fusion: a stupefying temperature of 6.5 Gigakelvin. Yes, that is 6.5 *billion* degrees kelvin.[62] On the other hand, FRC fusion offers notable decreases in complexity and cost over tokamaks like ARC due to its simple cylindrical shape.[63]

TAE is by far the most well funded fusion company with over $700 million raised over the past 22 years and backing coming from notable venture capital and innovation groups like Venrock, Vulcan, and Russian state-owned Rusnano.[64] To supplement investment, TAE is pursuing spinoff opportunities in the health space to help finance FRC fusion development.[65] TAE plans to break Q with the *Copernicus* D-T FRC reactor in 2023 and develop *Da Vinci*, a commercially scalable H-B11 FRC reactor, in the later half of this decade.[66]

General Fusion is an 18 year old firm based in British Columbia developing another novel approach to commercial fusion power called Magnetized Target Fusion (MTF) which combines aspects of magnetic confinement and inertial confinement.[67] The design revolves around an MTF chamber filled with a vortex of molten lead and lithium that D-T plasma is injected directly into and then compressed by massive steam pistons to achieve fusion: it is definitely the most metal approach to fusion.[68] Third only to TAE and CFS, General Fusion has raised over $190 million over the past 18 years with notable investments and support from the Malaysaisn Sovereign Wealth Fund and Bezos Expeditions.[69] General Fusion has stated that it has secured the necessary funding and partnerships to have a power plant scale demonstration of its reactor operational by 2023.[70]

At the surface level, it seems like **Commonwealth Fusion Systems** is late to the fusion industry and has target demonstration dates that are far behind TAE and General Fusion (GF); SPARC is planned to be operational by 2025 while TAE and GF plan to demonstrate their capabilities by 2023. In reality, CFS has a huge advantage with its ARC design. It is highly

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[60] "Clean, Safe, Abundant Fusion Energy." *TAE Technologies*, 4 Dec. 2020, tae.com/fusion-power/.
[61] "Fusion's Path to Practicality." *Energy.gov*, www.energy.gov/science/articles/fusions-path-practicality.
[62] Ibid.
[63] Ibid.
[64] "TAE Technologies - Funding, Financials, Valuation & Investors." *Crunchbase*, www.crunchbase.com/organization/tae-technologies/company_financials.
[65] Ibid.
[66] "Clean, Safe, Abundant Fusion Energy." *TAE Technologies*, 4 Dec. 2020, tae.com/fusion-power/.
[67] "Our Technology." *General Fusion*, generalfusion.com/technology-magnetized-target-fusion/.
[68] Dec 17, 2017 by Darrell Proctor. "Canadian Company Has Funding for Fusion Demonstration Plant." *POWER Magazine*, 18 Dec. 2019, www.powermag.com/canadian-company-has-funding-for-fusion-demonstration-plant/.
[69] "General Fusion - Crunchbase Company Profile & Funding." *Crunchbase*, www.crunchbase.com/organization/general-fusion.
[70] Dec 17, 2017 by Darrell Proctor. "Canadian Company Has Funding for Fusion Demonstration Plant." *POWER Magazine*, 18 Dec. 2019, www.powermag.com/canadian-company-has-funding-for-fusion-demonstration-plant/.

unlikely that either TAE or GF will break Q before the late 2020s. CFS on the other hand, has a good chance of breaking Q with SPARC in the mid to late 2020s and being the first mover in the commercialization of fusion power with ARC because D-T tokamaks are the most well-developed and understood way of achieving fusion, period; there is a reason why ITER is a D-T tokamak.[71] The designs employed by TAE and GF may suffer in later stages of development and operation because they lack the enormous body of scientific literature and understanding that exists for D-T tokamaks.

Finding a Target Levelized Cost of Energy

Finding a benchmark levelized cost of energy (LCOE) for an energy system that does not exist yet, neither commercially nor scientifically, is challenging and prone to error due to changes in energy markets and technology. That being said, finding this target is helpful for narrowing down the necessary price of energy that ARC must achieve in order to be competitive with other sources of energy. To find this target LCOE, different types of renewable energy will be analyzed and compared to fusion. The system that is the most comparable to fusion will be explained and balanced with current markets to set a necessary LCOE for ARC.

Although most forms of renewable energy might seem like a good comparison to fusion due to their minimal impact on the environment, many commentators have been lured into this trap; wind, solar, geothermal, and hydro are not good comparisons to fusion for two main reasons.[72] First, all of the aforementioned energy sources are region dependent and rely on special geographic and climatic attributes in conjunction with the use of transmission and storage technologies. You can only build solar farms in regions with high levels of solar insolation, and if a utility provider wanted to provide the power that is generated to population centers, which tend to be far away from regions with high renewable capacity, they would have to construct high voltage transmission lines over great distances.[73] A fusion plant can be built anywhere near a body of water for its steam cycle and will not require energy storage technologies due to its turbine system.

Second, with the exceptions of geothermal and hydro, renewables have a dispatchability issue. Due to their lack of a turbine and control of their own fuel source, they can not respond to power fluctuations based on grid demand.[74] D-T fusion power systems will be able to adjust their micro and macro output on demand, via a steam cycle driven turbine and the ability to control steady-state or pulsed fusion plasma.[75] This is not meant to disparage renewable energy technologies, which are undoubtedly going to be a larger part of the global energy production mix than fusion any time soon, but rather contrast them with fusion as an energy source.

[71] Brans, Pat. "Science: New Steady State Analysis." *ITER*, 24 Feb. 1970, www.iter.org/newsline/-/3401.
[72] Lovins, Amory B. "Fusion Power: The Case of the Wrong Competitors." *Forbes*, Forbes Magazine, 7 Sept. 2014, www.forbes.com/sites/amorylovins/2014/09/07/fusion-power-the-case-of-the-wrong-competitors/?sh=4a31f84a6c3b
[73] Thomas, Harry. "Interview with Dr. Scott Hsu." 20 Nov. 2020.
[74] Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.
[75] Ibid.

Fusion should also not be compared to potential grid scale hydrogen plants because hydrogen is more of an energy storage technology than a primary energy producer. Since there are no abundant natural sources of pure, diatomic hydrogen on Earth, it has to be synthesized from other resources like water.[76] Electrolysis, the process of splitting water into its component elements to create hydrogen, is energy intensive and therefore not a primary energy source like fusion.[77] Instead hydrogen should be considered as more of an energy storage mechanism, whereby excess energy from renewable sources and unused turbine inertia is converted into hydrogen for later use in grid scale hydrogen plants.

Unsurprisingly, the most comparable form of energy to nuclear fusion is nuclear *fission*, but the type of nuclear fission matters. Current Generation 2 and 3 fission reactors tend to be horribly uncompetitive due to sky high operating and construction costs that stem from their size and dated designs.[78] Generation 4 nuclear fission reactors overcome these issues through novel technologies that lead to significant reductions in the size and maintenance of fission plants while increasing efficiency and net energy production.[79] Theoretically, ARC's relatively modest nuclear fusion island will be more similar to cheaper, smaller, and efficient Gen 4 designs than older, larger fission reactors: which is what ITER scale commercial fusion would be comparable to. Out of all current plans for Gen 4 fission, NuScale's small modular reactor (SMR) is the most mature design; a power plant that utilizes 12 of these SMRs has already been planned to be constructed in Utah by 2033.[80] Because of these similarities in scale, primary energy production capacity, and technology, the most comparable current energy technology to ARC is NuScale's SMR.

Based on an analysis by Breakthrough Energy, NuScale's SMRs will have to be competitive with combined cycle (CC) natural gas if they are to succeed.[81] Breakthrough found that based on current performance and estimated construction costs of NuScale SMR plants, they can achieve this benchmark without the aid of subsidies or tax credits at a discount rate of 5% or lower.[82] This is promising for NuScale and important for ARC. If the assumption that NuScale SMRs are the most comparable system to ARC is true, then ARC must also have a similar LCOE to CC natural gas plants if it is to be competitive in future energy markets. According to the US Energy Information Agency, the projected LCOE of CC natural gas for 2025 is just under **$0.04/kWh**.[83] If ARC, or any fusion reactor for that matter, can achieve this LCOE, there is a good chance that it will be profitable, even without government aid.

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76 Thomas, Harry. "Interview with Dr. Scott Hsu." 20 Nov. 2020.
77 Ibid.
78 Ibid.
79 "Cost Competitive." *Cost Competitive Nuclear Technology | NuScale Power*, www.nuscalepower.com/benefits/cost-competitive.
80 Fletcher, Andrew, and Zeke Hausfather. "Can NuScale's SMR Compete With Natural Gas?" *The Breakthrough Institute*, 8 Sept. 2020, thebreakthrough.org/issues/energy/nuscale-vs-gas.
81 Ibid.
82 Ibid.
83 US Energy Information Administration. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2020*. 2020, www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

Considerations for Profitability

The target LCOE of \$0.04/kWh is simply intended to provide a rough benchmark for ARC to achieve. It is foolish to predict the future, and this paper has no intentions of testing that statement. Rather, the target LCOE set by CC natural gas in 2020 is an educated guess established by a chain of assumptions: that ARC will have comparable economics to NuScale SMRs and that NuScale SMRs will be competitive with CC natural gas. It is a quantitative way of saying that ARC must be competitive with Gen 4 fission which must be competitive with CC natural gas. Unfortunately, from the perspective of 2020, it is impossible to know if the technology for ARC will work and if it will be commercially scalable.

That being said, there are a host of dynamics that will affect the likelihood of the latter. Even if an ARC pilot reactor successfully implements the teachings of the SPARC test reactor and can produce a stable, high Q plasma, there are still many economic, operational, and political factors that will need to be considered before CFS produces grid-scale energy. A few of the most relevant dynamics for ARC are discussed below.

Legislation and Natural Gas Prices

The price of natural gas will play a major role in determining the economic viability of both Gen 4 fission and fusion. Given the shale boom, it is unlikely that natural gas prices will fall in the US any time soon.[84] This puts ARC in an unfavorable position for US markets because the \$0.04/kWh LCOE of CC natural gas may continue to fall in the future. However, climate oriented government policies that artificially raise natural gas prices and lower renewable prices may come to the rescue. Breakthrough's discount rate analysis of NuScale SMRs came to the conclusion that if the same level of tax credits that are currently extended to renewables were extended to the SMRs, they would be nearly two times as competitive with CC natural gas compared to pure market competition.[85] If the assumption holds that Gen 4 nuclear is comparable to ARC, then a similar tax credit for fusion would significantly increase ARC's profitability and scalability.

Carbon taxes and direct subsidies for fusion would also balance the LCOE equation and increase ARC's future competitiveness with CC natural gas. With the Biden administration and Democratic control of the House, and potentially the Senate, some sort of "carbon enforcement mechanism" can be expected within the next four years.[86] A carbon tax would increase the LCOE of CC natural gas and increase fusion's appeal in the wholesale energy market.[87] Similarly, recent bipartisan legislation in both chambers of congress to preserve and modernize

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[84] University of Texas. "The U.S. Shale Revolution." *The Strauss Center*, 19 June 2020, www.strausscenter.org/energy-and-security-project/the-u-s-shale-revolution/.

[85] Fletcher, Andrew, and Zeke Hausfather. "Can NuScale's SMR Compete With Natural Gas?" *The Breakthrough Institute*, 8 Sept. 2020, thebreakthrough.org/issues/energy/nuscale-vs-gas.

[86] "President-Elect Biden Supports a 'Carbon Enforcement Mechanism' - Could That Mean a Price on Carbon? - Environmental & Energy Law Program." *Harvard Law School*, 16 Nov. 2020, eelp.law.harvard.edu/2020/11/president-elect-biden-supports-a-carbon-enforcement-mechanism-could-that-mean-a-price-on-carbon/.

[87] Fletcher, Andrew, and Zeke Hausfather. "Can NuScale's SMR Compete With Natural Gas?" *The Breakthrough Institute*, 8 Sept. 2020, thebreakthrough.org/issues/energy/nuscale-vs-gas.

America's nuclear power capabilities indicates that fusion would be at least partially subsidized in the same way that older nuclear fission plants and renewables are today.[88] The subsidies would decrease the LCOE of fusion power and increase economic competitiveness for ARC.[89] It remains to be seen what will happen on the political front, but the rising force of climate legislation is an unequivocal boon for ARC and fusion as a whole.

Construction and Operations Cost

ARC's projected construction cost is unknown right now, but there are a few ways of deducing what it might be similar to. Once again, this conjecture will rely heavily on comparisons to existing and near future nuclear fission plants. Only 35% of a Gen 3 or lower fission plant's cost stems from its "nuclear island". The rest is devoted towards the facility, the steam cycle equipment, the turbines, heat sinks, etc.[90] While ARC will hopefully not be anywhere near as expensive as a current fission plant due to its form factor and inherent modularity, a majority of its capital cost will still come from auxiliary equipment and facilities. The same contractors that build this equipment for fission plants will likely be employed to build ARC's auxiliary equipment. Thus, the main cost lowering variable in a grid-scale ARC plant will be the reactor itself. With some luck, ARC's construction costs will be similar to those projected for Gen 4 nuclear plants like NuScale's Utah SMR facility.

In terms of operations, an ARC plant will also be comparable to a Gen 4 fission plant rather than a legacy Gen 3 or lower due to the incorporation of sophisticated automated nuclear control systems which require less staff. A minor critique of commercial fusion power stations is that they will require the small army of highly-skilled engineers that it takes to run a traditional fission plant.[91] This assessment does not take into account advances in control system technologies that will be implemented in advanced nuclear.[92] Similarly, maintenance costs will be notably lower in an ARC facility because the reactor as a whole is designed to be quickly upgraded and refurbished via its modular components. ARC, and fusion as a whole, will almost certainly require far fewer protective forces than legacy fission systems. Any significant maintenance costs will stem from auxiliary equipment.

Production and Disposal of Low-Level Nuclear Waste

Another minor critique of fusion power stations is that the volume of low-level nuclear waste that is created will be significant: over 70,000 metric tons over a projected 25 year plant lifetime.[93] Once again, ARC's molten salt bath comes to the rescue. The blanket will shield a

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[88] Dec 27, 2018 by Sonal Patel. "Bipartisan Nuclear Modernization Bill Clears Congress." *POWER Magazine*, 27 Dec. 2018, www.powermag.com/bipartisan-nuclear-modernization-bill-clears-congress/.

[89] Fletcher, Andrew, and Zeke Hausfather. "Can NuScale's SMR Compete With Natural Gas?" *The Breakthrough Institute*, 8 Sept. 2020, thebreakthrough.org/issues/energy/nuscale-vs-gas.

[90] Lovins, Amory B. "Fusion Power: The Case of the Wrong Competitors." *Forbes*, Forbes Magazine, 7 Sept. 2014, www.forbes.com/sites/amorylovins/2014/09/07/fusion-power-the-case-of-the-wrong-competitors/?sh=4a31f84a6c3b

[91] Ibid.

[92] Jun 6, 2018 by Sonal Patel. "NuScale Boosts SMR Capacity, Making It Cost Competitive with Other Technologies." *POWER Magazine*, 7 June 2018, www.powermag.com/nuscale-boosts-smr-capacity-making-it-cost-competitive-with-other-technologies/.

[93] An Energy Technology Distillatefrom the Andlinger Center for Energy and the Environment at Princeton University, Fusion Energy via Magnetic Confinement.

majority of reactor components from neutron erosion and decrease this amount by a factor of 50.[94] It remains to be seen if this is true in practice, but the molten salt blanket will unequivocally reduce the amount of nuclear waste produced by ARC and thus increase its profitability.

Even with this reduction however, ARC will still produce a large amount of low-level nuclear waste which generally needs to be stored for 10-100 years.[95] It has been projected that a majority of the cost of disposal for this waste will come from its extraction, with only 15% of the cost stemming from storage.[96] Although this might be true for scientific reactor designs like ITER, ARC's modularity and vertical lift access to the fusion core will significantly depress this cost.[97] The waste will be disposed of via existing infrastructure and logistics networks,[98] and there will likely have to be a significant expansion of the low-level nuclear waste industry if grid-scale fusion becomes reality.

Conclusion and Commercial Assessment

Based on the factors that work for and against the ARC's design and the commercialization of fusion power as a whole: ***CFS will likely break Q with the SPARC reactor by 2030, but it is unlikely that ARC fusion reactors will be commercially viable before 2040.***

High Possibility of Breaking Q Before 2030

CFS has a feasible and stable plan that is built on a well-understood design enabled by promising new technologies, a productive and synergistic collaboration with MIT PSFC, and ample funding from reliable sources. SPARC, or some iteration of it, will likely break Q before 2030 through the enabling use of ReBCO HTS magnets and a mature understanding of tokamak physics. Even if the reactor doesn't immediately break Q in 2025, the modularity and planned components for the reactor will allow for fast, iterative improvement of SPARC as a whole. *Given the slow progress of ITER and the technological uncertainties of CFS' direct competitors, there is a good chance that* ***SPARC will be the first fusion reactor in history to break Q.***

Low Possibility of Commercial Viability Before 2040

That being said, given the necessary levels of capital, technological development, and infrastructure required to scale SPARC to ARC, it is highly unlikely that a commercial ARC fusion plant will be producing grid-scale power before 2035. Although CFS' timeline indicates a potential roll out by 2033, the iterative improvement process allowed for by ARC's modular design will depress development and scaling time horizons, and climate legislation will likely provide a favorable landscape for fusion, there are simply too many unknown variables and challenges to overcome before a successful grid-scale pilot plant. It is extremely unlikely that a

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[94] Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.

[95] An Energy Technology Distillatefrom the Andlinger Center for Energy and the Environment at Princeton University, Fusion Energy via Magnetic Confinement.

[96] Ibid.

[97] Plasma Science and Fusion Center, MIT. "Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure)." *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.

[98] An Energy Technology Distillatefrom the Andlinger Center for Energy and the Environment at Princeton University, Fusion Energy via Magnetic Confinement.

technology that is not scientifically viable today will be commercially viable within the next 13 years. However, given ARC's exceptional design and robust team, it is the opinion of the author that ***CFS will be the first to commercialize fusion with ARC in the early 2040s*.**

Bibliography

All-the-Worlds-Tokamaks, www.tokamak.info/.

Brans, Pat. “Science: New Steady State Analysis.” *ITER*, 24 Feb. 1970, www.iter.org/newsline/-/3401.

“Clean, Safe, Abundant Fusion Energy.” *TAE Technologies*, 4 Dec. 2020, tae.com/fusion-power/.

“Commonwealth Fusion - Crunchbase Company Profile & Funding.” *Crunchbase*, www.crunchbase.com/organization/commonwealth-fusion-systems.

“Commonwealth Fusion - Funding, Financials, Valuation & Investors.” *Crunchbase*, www.crunchbase.com/organization/commonwealth-fusion-systems/company_financials.

“Cost Competitive.” *Cost Competitive Nuclear Technology | NuScale Power*, www.nuscalepower.com/benefits/cost-competitive.

Dec 17, 2019 by Darrell Proctor. “Canadian Company Has Funding for Fusion Demonstration Plant.” *POWER Magazine*, 18 Dec. 2019, www.powermag.com/canadian-company-has-funding-for-fusion-demonstration-plant/.

Dec 27, 2018 by Sonal Patel. “Bipartisan Nuclear Modernization Bill Clears Congress.” *POWER Magazine*, 27 Dec. 2018, www.powermag.com/bipartisan-nuclear-modernization-bill-clears-congress/.

Deign, Jason. “MIT Validates Science Behind New Nuclear Fusion Reactor Design.” *Greentech Media*, Greentech Media, 20 Oct. 2020, www.greentechmedia.com/articles/read/mit-validates-science-behind-proposed-cfs-fusion-reactor?utm_campaign=gtmsocial.

An Energy Technology Distillatefrom the Andlinger Center for Energy and the Environment at Princeton University, *Fusion Energy via Magnetic Confinement*.

Fletcher, Andrew, and Zeke Hausfather. “Can NuScale's SMR Compete With Natural Gas?” *The Breakthrough Institute*, 8 Sept. 2020, thebreakthrough.org/issues/energy/nuscale-vs-gas.

Fountain, Henry. “Compact Nuclear Fusion Reactor Is 'Very Likely to Work,' Studies Suggest.” *The New York Times*, The New York Times, 29 Sept. 2020, www.nytimes.com/2020/09/29/climate/nuclear-fusion-reactor.html.

"Fusion Power." *Fusion Power - an Overview | ScienceDirect Topics*, www.sciencedirect.com/topics/engineering/fusion-power.

"Fusion's Path to Practicality." *Energy.gov*, www.energy.gov/science/articles/fusions-path-practicality.

"General Fusion - Crunchbase Company Profile & Funding." *Crunchbase*, www.crunchbase.com/organization/general-fusion.

Goldston, Robert. "Why Fusion?" *Bulletin of the Atomic Scientists*, 26 Aug. 2020, thebulletin.org/2018/04/why-fusion-2/.

"ITER Members." *ITER*, www.iter.org/proj/Countries.

Jassby, Daniel. "Fusion Reactors: Not What They're Cracked up to Be." *Bulletin of the Atomic Scientists*, 24 Aug. 2020, thebulletin.org/2017/04/fusion-reactors-not-what-theyre-cracked-up-to-be/.

Jun 6, 2018 by Sonal Patel. "NuScale Boosts SMR Capacity, Making It Cost Competitive with Other Technologies." *POWER Magazine*, 7 June 2018, www.powermag.com/nuscale-boosts-smr-capacity-making-it-cost-competitive-with-other-technologies/.

Lovins, Amory B. "Fusion Power: The Case of the Wrong Competitors." *Forbes*, Forbes Magazine, 7 Sept. 2014, www.forbes.com/sites/amorylovins/2014/09/07/fusion-power-the-case-of-the-wrong-competitors/?sh=4a31f84a6c3b.

"Major next Steps for Fusion Energy Based on the Spherical Tokamak Design." *Princeton Plasma Physics Lab*, www.pppl.gov/news/2016/08/major-next-steps-fusion-energy-based-spherical-tokamak-design.

Molavi-Choobini, Ali Asghar, et al. "Study of Lower Hybrid Current Drive for the Demonstration Reactor." *Nuclear Engineering and Technology*, Elsevier, 26 Feb. 2016, www.sciencedirect.com/science/article/pii/S1738573316000632.

"Nuclear Fusion Power." *Nuclear Fusion : WNA - World Nuclear Association*, 2020, www.world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.aspx.

"Our Technology." *General Fusion*, generalfusion.com/technology-magnetized-target-fusion/.

Plasma Science and Fusion Center, MIT. “Fusion Energy Smaller. Sooner. Smarter. (ARC Brochure).” *MIT.edu*, 2018, www.psfc.mit.edu/files/psfc/imce/research/topics/sparc/MITSPARCbrochure.pdf.

“President-Elect Biden Supports a ‘Carbon Enforcement Mechanism’ - Could That Mean a Price on Carbon? - Environmental & Energy Law Program.” *Harvard Law School*, 16 Nov. 2020, eelp.law.harvard.edu/2020/11/president-elect-biden-supports-a-carbon-enforcement-mechanism-could-that-mean-a-price-on-carbon/.

Sorbom, B.N., et al. “ARC: A Compact, High-Field, Fusion Nuclear Science Facility and Demonstration Power Plant with Demountable Magnets.” *Fusion Engineering and Design*, North-Holland, 14 July 2015, www.sciencedirect.com/science/article/abs/pii/S0920379615302337?via=ihub.

“SPARC.” *SPARC | Research | MIT Plasma Science and Fusion Center*, www.psfc.mit.edu/sparc.

“TAE Technologies - Funding, Financials, Valuation & Investors.” *Crunchbase*, www.crunchbase.com/organization/tae-technologies/company_financials.

“Technology.” *Technology | Commonwealth Fusion Systems*, cfs.energy/technology/.

Thomas, Harry. “Interview with Dr. Scott Hsu.” 20 Nov. 2020.

University of Texas. “The U.S. Shale Revolution.” *The Strauss Center*, 19 June 2020, www.strausscenter.org/energy-and-security-project/the-u-s-shale-revolution/.

US Energy Information Administration. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2020*. 2020, www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

“Vacuum Vessel.” *ITER*, www.iter.org/mach/vacuumvessel.

Zohm, Hartmut. “On the Size of Tokamak Fusion Power Plants.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 377, no. 2141, 2019, p. 20170437., doi:10.1098/rsta.2017.0437.