Hammering Stars: General Fusion's Method for Fusion Energy

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1 Introduction

Fusion power has long been the ultimate power source. It produces negligible pollution, runs consistently, and the main fuel, deuterium, is cheap and nearly endless. The problem has always been execution. Fusion requires incredibly high temperatures to occur, and these states are very difficult to create and contain. There are also multiple other engineering challenges, such as the abundance of high energy neutrons, which must be solved. One method, originally proposed by the Naval Research Laboratory in their LINUS project, is Magnetic Targeted Fusion (MTF)[1]. This method involves initially creating a low temperature plasma generally with standard magnetic containment and heating methods. The plasma is then injected into the compression chamber where a metal liner compresses the plasma. The liner never actually touches the plasma, but rather the metal liner acts as a flux conserver. As compression occurs the inductance goes down so the magnetic field must increase to conserve flux. This growing magnetic field compresses the plasma by increasing the magnetic pressure that contains the plasma[2].

The company General Fusion is one of a few promising fusion power startups to develop over the past decades. They are trying to achieve commercially viable fusion through MTF. Started in 2002, by Dr. Michel Laberge, they have spent many years developing this technology and gaining experience in fusion development. They have been successful in raising capital to fund this research, bringing in close to 200 million dollars so far[3]. Over their nineteen year history they have made a lot of progress in the fields of plasma physics and fusion energy engineering. They showed themselves to be an adaptable company when they made significant changes to their reactor concept in 2017 in order to avoid some results which made commercial viability impossible. Although their method is yet unproven, and they face multiple difficult challenges, they have had some promising results so far which indicate this reactor concept could eventually be commercially viable[4].

[1] Aaron Froese et al. "Effects on Stable MHD Region of a Magnetized Target Plasma Compression". In: 62th Annual Meeting of the APS Division of Plasma Physics (Nov. 9, 2020). eprint: `CP19.22`.

[2] Aaron Froese et al. "Stable compression of a spherical tokamak plasma". In: *Nuclear Fusion* 60 (4 2020). DOI: `https://doi.org/10.1088/1741-4326/ab74a2`.

[3] *Organization, General Fusion.* URL: `https://www.crunchbase.com/organization/general-fusion`. (accessed: 04.18.2021).

[4] *Company Profile.* URL: `https://generalfusion.com/company-profile/`. (accessed: 04.15.2021).

2 General Fusion's Approach

General Fusion's method of producing fusion energy includes a couple key parts. First are the plasma injectors, which create the initial plasma and inject it into the chamber to be compressed. Second is the liquid metal wall which serves a variety of functions including acting as a flux conserver to compress the plasma. Finally there are the pistons which compress the liner to bring the injected plasma to fusion temperatures and densities. All components of the system are still deep in development and as such the details of these devices are not fully determined. Test devices have been developed, the characteristics of which will be examined, and an integrated prototype is currently being built which will combine all the components into a single testing system. This integrated prototype is meant to be the precursor to their full scale demonstration plant[5].

General Fusion has a long history of research and development into plasma formation and injection. They have built multiple small scale devices, the latest of which are the Spector's 1-5. They have also built three reactor scale injectors for larger scale testing. The third of those, PI3 is currently actively used for testing of plasma formation. PI3 is a very capable device, able to produce plasma targets over 400eV and with a lifetime of 3.5ms, which is approximately the conditions required for targets used in the final reactor. As PI3 is already so capable, the technology in the injectors of the final reactor will likely be very similar. PI3 uses fast Coaxial Helicity Injection (CHI), to form the spherical tokamak plasma. The plasma maintains magnetic confinement from that point onward, through injection and compression, only by the currents in the plasma and in the flux conserving wall. To initiate the plasma formation requires massive capacitor banks which use a total of 7.6 MJ of energy per formation with a max current of 1.2 MA. PI3 is currently being used to study variations in confinement time and wall interactions, found when other parameters like temperature are varied[6].

The liquid metal wall is another crucial component which serves many purposes. Currently it is proposed to be made of a lithium-lead mixture, specifically 83% lead and 17% lithium. That mixture was found to have both the best properties for the situation and some practical benefits[7]. This mixture has a low melting point and high vapor pressure, both useful for maintaining the metal in its liquid state. It also has the major advantage of being less chemically reactive than pure lithium which makes it safer and easier to handle. This liquid will be formed into a vortex by injecting a current, and by pumping the liquid metal in and out of the vessel. These two combined will hold the metal up against the outer walls and establish a cavity for the plasma to be injected into. The wall serves four purposes. First the lithium in the wall can absorb and react with the neutrons produced from the fusion reactions. Lead multiplies the neutrons which Lithium reacts with to produce tritium, solving the tritium supply problem. Second, the metal vortex also serves as a first wall, protecting the rest of the reactor structure from the heat of the plasma along with the damaging neutrons and other particles. Third, the wall serves as a flux conserver which is essential for any spherical tokamak. Finally the wall is used as a means of removing the heat produced in the fusion reactions. Because this liquid metal is in such close contact with the plasma it absorbs the heat produced, and then when it is pumped out it can be run through a heat exchanger to heat steam. This steam can then be used to produce electrical power via a traditional generator, or it can be fed back in to operate the pistons[8]. By using the liquid metal wall as the heat transport fluid they increase the efficiency of energy production and the possibility for contact between the lithium and water

[5]Peter O'Shea et al. "Magnetized Target Fusion at General Fusion: An Overview". In: 9th International Congress on Plasma Physics (Vancouver, Canada, June 5–8, 2018).

[6]K. Epp et al. "Recent Progress in the Plasma Injector 3 Spherical Tokamak Program". In: 60th Annual Meeting of the APS Division of Plasma Physics (Portland, Oregon, Nov. 5–9, 2018). eprint: CP11.00192.

[7]Michel Laberge et al. "Acoustically driven Magnetized Target Fusion". In: *IEEE Transactions on Plasma Science, 2013 IEEE 25th Symposium on Fusion Engineering (SOFE)* 42 (June 2013), pp. 1–7. DOI: 10.1109/SOFE.2013.6635495.

[8]Michel Laberge. "Magnetized Target Fusion with a Spherical Tokamak". In: *Journal of Fusion Energy* 38 (2019), pp. 199–203. DOI: https://doi.org/10.1007/s10894-018-0180-3.

used for energy generation is minimized because of the high level of lead dominating the mixture.

The wall is being tested with the Spector Lithium Configuration (SLiC) injector device. This device is very similar to the 5 SPECTOR devices, small scale plasma injectors, created by General Fusion for rapid testing. This device includes a liquid lithium blanket system. The lithium starts as a solid puddle in the bottom of the reactor. The lithium is hit with a 200kA current which liquefies it and creates a tsunami pushing the liquid up the wall into a hemisphere shape which covers the wall. This device does not involve any compression, as it is just designed to determine the interactions between the lithium wall and the plasma, and to show that a spherical tokamak plasma can be formed onto this moving lithium surface. Experiments with this device have shown that this formation is possible. They have also shown that including lithium of any sort, hot/cold, thin/thick, has positive effects on the lifetime of the plasma. Specifically, the liquid lithium was found to be more effective at improving the lifetime than solid[9]. While these results have been promising there have also been some possibly concerning plasma-surface interactions observed. More experiments with the SLiC and other devices are required to understand these interactions and how to solve them.

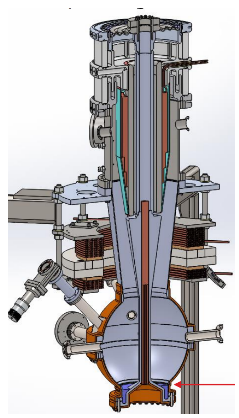

Figure 1: Render of the SLiC device. The lithium puddle is at the bottom where the red arrow points. The injector is at the top and fires the plasma into the 20cm radius vessel below.

Along with the SLiC device they have also tested the wall's properties using the piston test stand, which focuses on the pistons and their interactions with the wall. In order to better understand the wall and its interactions with the plasma, they are conducting extensive fluid and Magnetohydrodynamic (abv: MHD, the model used to study charged fluids) simulations. They are also conducting experiments into the overall dynamics of compressing a spherical cavity of liquid. These experiments currently use water but will eventually transition to using the liquid metal alloy Galinstan[10], which is composed of Gallium, Indium, and Tin[11]. All of these methods address the various interactions between the wall and other components and the effects the wall has on the achievement of net fusion energy.

The piston compression system is General Fusion's most unique component. In the original design each piston is propelled by high pressure air, and impacts an anvil at up to 50 m/s. The impact with the anvil generates a large amplitude acoustic pulse, which then propagates through the metal wall and plasma compressing them on a timescale of about 0.1ms. The piston motion is controlled by servo motors and an electronic braking system that are intended to allow for synchronized impacts within 2 μs of each other. To

[9] Stephen Howard et al. "Plasma-wall interaction on the SLiC spherical tokamak device with large-area, dynamic liquid lithium free surface". In: 62th Annual Meeting of the APS Division of Plasma Physics (Nov. 10, 2020). eprint: CP11.00192.

[10] O'Shea et al., "Magnetized Target Fusion at General Fusion: An Overview".

[11] Terence Bell. *Profile of the Metal Galinstan*. URL: https://www.thoughtco.com/what-is-galinstan-2340177. (accessed: 05.19.2021).

test this system multiple small pistons were built along with a large test system with a 1m radius chamber and 14 pistons[12]. This is the piston test stand mentioned previously. The commercial plant however was envisioned to have over 200 of these pistons operating at similar or better accuracy's[13]. After the testing of these systems, along with other tests and simulations of plasma stability, General Fusion reassessed their concept in 2017. The original design had issues with high magnetic fields vaporizing the wall. This is problematic first because the vapor affects the magnetic fields and therefore containment of the plasma. Also, the vapor can be picked up by the plasma, introducing impurities which add to the radiation losses, cooling the plasma. Along with the considerations for the wall, the old design required them to deal with having a high energy acoustic shock wave. This is problematic to have involved in the process, as if it is not perfectly applied it can destabilize the plasma.

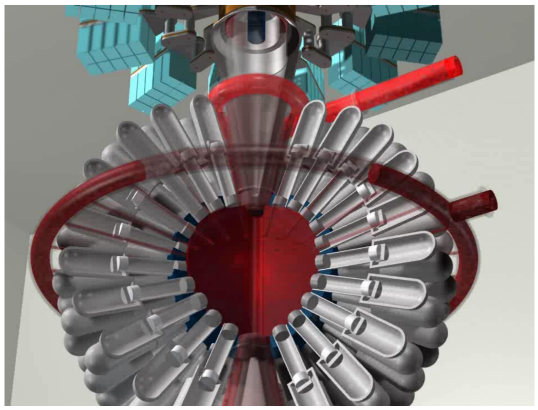

Figure 2: Rendering of the original reactor concept[15], the anvils can be seen in dark gray at the end of each piston tube.

The new design avoids these issues by removing the anvils so now the pistons are in direct contact with the metal liner. This is apparent in Figure 3 which shows the new reactor with the black pistons pressing on the light gray liquid metal. Contrast that with Figure 2 where the liner would sit in the red area and be impacted by the anvils shown at the end of the tubes in dark gray. This new concept functions at lower energy density and slower compression speeds with the pistons smoothly pushing the metal inwards to compress the plasma. This change from an acoustic pulse has allowed them to better stabilize the cavity of liquid metal in a spherical formation. The downside is the slower compression means higher energy confinement times. In order to achieve this new constraint General Fusion has moved to a spherical tokamak shape for their plasma target[16]. Along with the adoption of this new design General Fusion has begun building a fully integrated prototype reactor. This reactor will include all the elements discussed so far. The plasma will be created by an injector similar to PI3 and injected into a 1.5m chamber. In this chamber will be a lead-lithium liner to be compressed by the pistons in about 3.5ms.

[12] Laberge et al., "Acoustically driven Magnetized Target Fusion".

[13] Michael Delage. *Timing Is Everything: Pushing Fusion Forward with Pistons and Cutting-Edge Electronics*. Nov. 21, 2020. URL: `https://generalfusion.com/2018/11/timing-everything-pushing-fusion-forward-pistons-cutting-edge-electronics/`. (accessed: 4.13.2021).

[16] P. O'Shea et al. "Magnetized Target Fusion at General Fusion: An Overview". In: 62th Annual Meeting of the APS Division of Plasma Physics (Milwaukee, Wisconsin, Oct. 23–27, 2017).

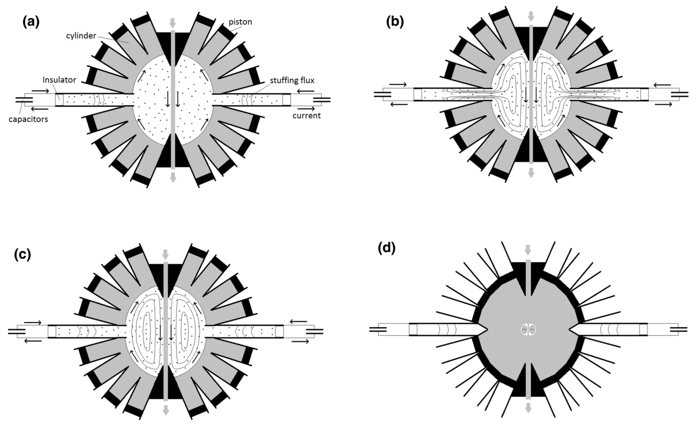

Figure 3: Diagram of the new reactor concept[18], plasma injectors are on each side, liquid metal is in light gray.

3 Challenges

General Fusion has faced and continues to face many difficult challenges in their quest to develop viable fusion power. One they have mostly solved is timing. In order to evenly compress the plasma and keep it stable the pistons need to strike at the correct time, with little room for error. Early in the design this was a major challenge but with the improvements over the past 10 years in control electronics and higher speed servos[19], they have been able to reduce the margin of error from more than $\pm 10\mu s$[20] to $\pm 2\mu$s[21]. With compression time at 3.5ms the current margin for error is well within the acceptable range as it is quite small compared to the compression time[22]. Currently they are working mostly on maintaining stable plasma throughout compression, and on improving the metal wall.

The wall presents a few difficult challenges mainly the various ways in which the material from the wall gets into the plasma. This is problematic because it can seriously effect the life of the plasma. Both the lead and lithium from the wall increase radiation in the plasma, making it harder to maintain the necessary temperatures. The wall also introduces other engineering challenges outside of the direct problem of plasma compression and energy generation. During operation the wall will be around $400°C$ which means the equipment to pump the wall mixture out, process it, and return it to the vortex must be able to withstand these temperatures. Furthermore, the processing of the mixture is no easy task. Tritium must be removed for re-injection which can be complicated as the radioactivity of the tritium means safety concerns are paramount. Also impurities are introduced into the mixture from neutrons activating the lead. This process produces $^{209}\mathbf{Bi}$ which decays into $^{210}\mathbf{Po}$ which is extremely radiotoxic. In order maintain safe reactor operation bismuth must be readily removed to prevent buildup of polonium and any polonium which is created must be removed and carefully dealt with[23]. Furthermore, the short timescales involved mean the material must be transported in and out of the reactor quickly yet the high mass of the material means large amounts of momentum are involved and the system must be able to

[19] Delage, *Timing Is Everything: Pushing Fusion Forward with Pistons and Cutting-Edge Electronics.*

[20] Michel Laberge. "Experimental Results for an Acoustic Driver for MTF". in: *Journal of Fusion Energy* 28 (June 209), pp. 179–182. DOI: 10.1007/s10894-008-9181-y.

[21] Dr. Michel Laberge. "Fusion Energy Progress at General Fusion". In: Pacific Energy Innovation Association (Vancouver, BC, Sept. 12, 2018).

[22] O'Shea et al., "Magnetized Target Fusion at General Fusion: An Overview".

[23] Paul W. Humrickhouse et al. "The Impacts of Liquid Metal Plasma-Facing Components on Fusion Reactor Safety and Tritium Management". In: *Fusion Science and Technology* 75.8 (2019), pp. 973–1001. DOI: 10.1080/15361055.2019.1658464.

safely handle that momentum magnitude without leaks[24].

The SLiC device discussed earlier has produced positive results in that they were able to form a plasma on the the lithium surface, but some issues were found as well. The experiments found that the plasma caused ripples with a wavelength of 5mm to form on the surface and grow in amplitude throughout the plasma lifetime[25]. This is concerning because if the surface can be disturbed enough the tops of these ripples could break off into the plasma causing increased radiation. The variation in surface geometry of the liner could also affect the magnetic fields generated by the liner thereby affecting the plasma stability.

Aside from the challenges the wall presents logistically and in its direct interaction with plasma, there are also challenges to be solved in the dynamics of the wall's compression. The liner is compressed by a pressure wave which is created by the pistons pushing on the liner. This wave is not uniform as it is made up of individual waves created by each piston, which then combine in the liquid metal. The analysis done by General Fusion on this problem was done based on the original reactor design. These problems are likely much more impactful in that case as the pulse generated by the piston striking on the anvil is much more disruptive than the pulse generated by the pistons just pushing on the liquid itself. That being said, there still is a pressure wave formed and as such this analysis will still apply to some degree. Their analysis shows the non-uniformity of the wave is both good and bad. It allows the compression cavity geometry to be altered depending on the piston impacts but if it is not done very precisely it can be extremely problematic. The velocity varying along the edge means the compression could be uneven causing issues with the plasma stability as it is compressed unevenly. The velocity variation may also cause cavitation[26]. Cavitation is where a liquid, in this case liquid PbLi, goes below its vapor pressure creating a bubble of gas. These bubbles generally collapse as the pressure around them shifts and this collapse can cause a shockwave[27]. This is a hazard which should be avoided as those shockwaves could affect the plasma stability, launch debris into the plasma, or damage the pistons. Aside from the non-uniformity, cavitation is also caused by the reflection of the pulse at the metal-plasma interface which leads to cavitation very close to the surface[28]. This is especially problematic as it can cause the surface of the wall to turn to spray which would introduce large amounts of impurities into the plasma. These challenges, although partially solved by the new reactor design, are still present and of concern if the pistons do not operate perfectly.

The biggest challenge for General fusion is the same as it is for all fusion programs, to maintain a stable plasma long enough to generate significant amounts of energy. They have readily solved the problem of creating the plasma with PI3 so now they specifically face the challenge of maintaining this plasma while quickly compressing it. The team has been developing simulations to study the plasma and determine the optimal geometry and initial parameters. This will also give them information on how they might modify the reactor to better fit within the stable range for the plasma. Plasma is by nature difficult to model because of the number of particles and short time scales involved. This led them to construct their model as a series of equilibrium states of the plasma generated by a plasma modeling tool called CORSICA. The idea of fusion through compression relies on having adiabatic compression. Although the compression in real life is unlikely to be fully adiabatic it can be estimated as such because of the time scales involved. The compression is quite fast compared to the movement of heat and magnetic flux, which allows is to be approximated as adiabatic in that sense, while also being much slower than the movement of the plasma particles themselves so that it may be considered mechanically adiabatic. Each state maintains

[24] UWFDM-994 Bibliography of a Promising Tritium Breeding Material - Pb83Li17. "UWFDM-994 Bibliography of a Promising Tritium Breeding Material - Pb83Li17". In: *University of Wisconsin Fusion Design Memos* 994 (1995).

[25] Howard et al., "Plasma-wall interaction on the SLiC spherical tokamak device with large-area, dynamic liquid lithium free surface".

[26] V. Suponitsky et al. "Pressure Wave in Liquid Generated by Pneumatic Pistons and Its Interaction with a Free Surface". In: *International Journal of Applied Mechanics* 09 (2017), p. 1750037.

[27] Phillip Eisenberg. *Cavitation*. Nov. 21, 2020. URL: `https://web.mit.edu/hml/ncfmf/16CAV.pdf`. (accessed: 4.22.2021).

[28] Eisenberg, *Cavitation*.

the same entropy, agreeing with the adiabatic approximation, and safety factor profiles and is identified by C, the compression ratio. From these constraints they can determine other parameters such as pressure and magnetic field profiles. Using this model they tested many different chamber geometries and plasma profiles. Figure 4 shows a visual depiction of one of these model computations. This set of states is special because they have high current density profiles on the edges, and a radially decreasing temperature profile. These two conditions imply a high level of stability for the plasma[29].

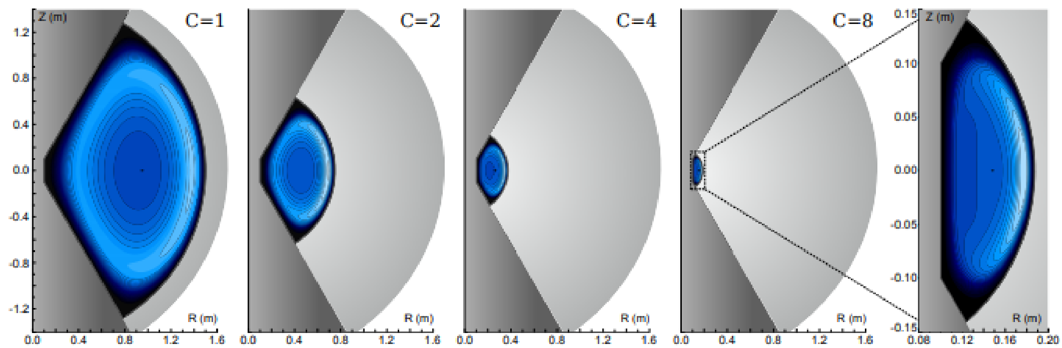

Figure 4: Shows the CORSICA equilibrium states. Light gray is liquid metal. The blue gradient represents the variation in parallel current density $J_{\|}/B$[31]

The model was used study a few different sources of instability. First is the change in the geometry of the plasma at high compression. For the first couple of stages the plasma compresses self-similarly but close to the shaft the plasma elongates because the shaft radius (R_s) is no longer small compared to the plasma radius. This is mainly problematic for simulating compression which it makes much more difficult to do accurately, but it could also have an effect on the stability of the plasma. Specifically the deformation of the plasma leads to less compression overall, which could lead to lower temperatures and thus less fusion energy produced. One solution to this, proposed by Michel Laberge, is to have the center shaft also made of liquid metal so that the shaft can change shape to accommodate the plasma. While this method may work, it introduces further difficulty in the design of the wall and how the cavity is formed[32].

They have also found that the initial current profile and the level of skin current, current near the edge of the plasma formed by reversal of the current profile in that area, can both be important to stability throughout compression. Initial profiles which are high near the edges were specifically found to be quite stable. This adds another challenge to their work with plasma injectors in that they will likely have to be able to produce plasma with a specific initial current profile in order to have high stability. As the edge current levels can be controlled by ramping the current in the center shaft they have analyzed various levels of shaft current to better understand the effects of this skin current. It was found to have significant effects on stability. This adds challenge to the overall reactor design in that the capability to alter the shaft current will be necessary to control this skin current and maintain stability[33].

Figure 5 shows a stability map for the compression scenario shown in Figure 4. Both resistive and ideal MHD instability are shown. These are two different categories of instabilities with ideal referring mostly to larger scale instabilities found through the ideal MHD equations while resistive instability comes from including dissipation into the ideal MHD equations[35]. The light blue line shows the stable corridor they

[29] Froese et al., "Stable compression of a spherical tokamak plasma".
[32] Froese et al., "Stable compression of a spherical tokamak plasma".
[33] Froese et al., "Stable compression of a spherical tokamak plasma".
[35] *Plasma Instabilities*. Sept. 7, 2012. URL: https://w3.pppl.gov/~jchen/B2012_6_instability_white.pdf. (accessed:

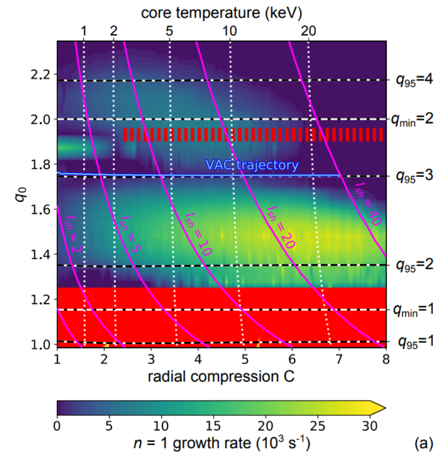

Figure 5: Stability map, Red is ideal MHD instability, and Green is resistive instability.[34]

found. This indicates there is a stable plasma compression path. The researchers also acknowledge that this analysis is not perfect with some factors being left out such as plasma rotation, and general kinetic effects. This research does not guarantee that the plasma can be stable through compression and as such General Fusion must continue with the difficult challenge of improving their models. That being said it shows that it is at least theoretically possible to maintain a stable plasma throughout compression.

4 Viability

Taking into account the components of the design and the challenges faced by General Fusion, a general idea of the viability of their concept can be determined. The integrated prototype reactor is not intended to reach breakeven, but it is the closest approximation to the full reactor which has been created so far. In order to demonstrate General Fusion's progress towards commercial viability an $N\tau$ calculation can be preformed based on the published information about the integrated prototype. This calculation will show how close the reactor is to net energy or what the energy gain is if the break even point is passed. The general equation for this calculation is[36]:

$$N\tau \geq \frac{\frac{3}{2}(N_i T_i + N_e T_e)}{\eta \frac{<\sigma v>_{dt}(T)}{4} Q_{dt} - (1-\eta)(A_{br}\sqrt{T} - \frac{A_{cyc} B_{comp} T}{N})}$$

The efficiency is not published by General Fusion, so it is chosen as $\eta = \frac{1}{3}$ since this is a reasonable general estimation. The following parameters are used as provided in the 2018 presentation "Magnetized Target Fusion at General Fusion: An Overview": Compression ratio, C = 10, initial magnetic field, $B_o = 0.6T$, final plasma density, $N = 6.5 * 10^{22}$, and the final β is 0.5.

B_{comp} which is the magnetic field strength at maximum compression is determined by the scaling laws. For spherical tokamak targets in MTF the scaling law for B is $\frac{B}{B_o} = C^2$. This gives $B_{comp} = 60T$. This

5.20.2021).

[36] A.A. Harms, K.F. Schoepf, and D.R. Kingdon. *Principles of Fusion Energy: An Introduction to Fusion Energy for Students of Science and Engineering.* World Scientific, 2000. ISBN: 9789812380333. URL: `https://books.google.com/books?id=DD0sZgutqowC`.

field is low enough to avoid the issue of wall material evaporating found in the old reactor design as that threshold is $\sim 100T$. Using B_{comp}, N, and β with the standard magnetic confinement equation we can solve for an equation for plasma temperature, T. This calculation assumes $T_e = T_i$ as no separate values are provided. While this computed value for T does not necessarily represent actual reactor conditions the number provided by General Fusion for final plasma temperature is $\geq 10keV$ and so this calculation is will give an upper bound to that range:

$$\beta \frac{B^2}{2\mu_o} \geq N_i kT + N_e kT$$
$$68.9 \geq T$$
$$68.9kev \geq T \geq 10kev$$

This is a very high T value which will not be reached in the reactor. The functional form of $< \sigma v >$ can be found in "Controlled Thermonuclear Reactions"[37]. This equation is only accurate up to 20 keV and since the temperature is unlikely to go much past 20 keV, T will be kept within this range as it is more accurate to use this form than to obtain values from a graph of $< \sigma v >$:

$$< \sigma v >_{dt} (T) = \frac{3.68 * 10^{-12}}{T^{2/3}} \exp(\frac{-19.94}{T^{1/2}})$$

Taking this range 20keV $\geq T \geq$ 10keV the $N\tau$ values can be plotted in figure 6. These values are then compared with the $N\tau$ value which can be calculated by taking τ as 0.5ms. This is the time of fusion energy production given in Michel Laberge's paper describing the spherical tokamak MTF concept.

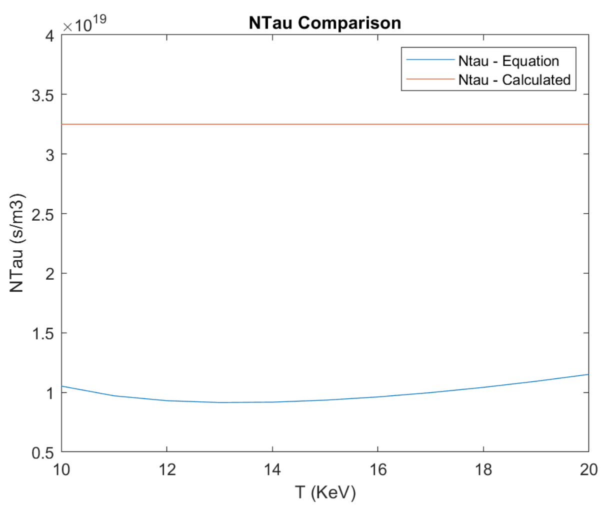

Figure 6: $N\tau$ plot, Blue is the $N\tau$ generated by the equation, and Red is the $N\tau$ generated by multiplying the proposed N and τ values.

This analysis shows that a reactor operating under these parameters would produce net energy across the whole range of possible temperatures. This analysis however does not take into account many of

[37] Samuel Glasstone and Ralph H. Lovberg. *Controlled thermonuclear reactions : an introduction to theory and experiment.* Van Nostrand Reinhold Co., 1975.

the challenges discussed previously. It also relies on τ value which is not based on actual experimental results but rather an estimation. The paper which proposed that estimation also includes calculations for the energy output of a theoretical spherical tokamak MTF reactor based on the General Fusion design. Although the previous calculation shows gains of ~ 3.5 the paper proposes a gain of ~ 1. This gain figure is reasonably accurate for the parameters of the reactor in the paper, and as such is likely more accurate than the number derived from the above calculation. This number is concernedly low as when factoring in the rest of the operation costs it will be difficult to achieve commercial viability while only producing slightly more energy than what is put in. Specifically, Laberge sates that the total work that must be provided to the plasma is 137 MJ while the energy produced would be approximately 140 MJ. He adds that additional tritium breeding reactions in the liquid metal will produce another 32 MJ. Although this helps somewhat to improve the energy generation of the reactor the main factor that can decrease energy usage is how much of the compression energy can be recovered[38]. When the pressure pulse hits the liquid metal-plasma interface the majority of it is reflected because of the variation in acoustic impedance between the metal and the plasma[39]. This reflected pulse can provide much of the energy to reset the pistons, increasing the efficiency of the reactor. If there was enough pressure produced by the plasma to fully reset the pistons even more energy could be saved but as it is uncertain whether or not this would be possible, this paper estimates that 80% is recovered. This means only 27 MJ of the 137 MJ put into the plasma stays there and the other 110 MJ will be recovered and therefore only needed for the startup of the reactor and not during continuous operation. This leads to the total energy left in the wall:

$$140\text{MJ Fusion Energy } + 27\text{MJ Mechanical Energy } + 32\text{MJ Extra Reactions Energy } = 200\text{MJ}$$

From this 200 MJ the formation of the next plasma target will require approximately 11 MJ and as mentioned previously the pistons will need 27 MJ to compress this new target. Laberge assumes a Carnot efficiency of 40%, a very achievable value compared the average power plant in existence today. As such we have:

$$200\text{MJ} \times 40\% = 80\text{MJ} - 27\text{MJ} - 11\text{MJ} = 42\text{MJ}$$

The timing of this cycle is proposed by Laberge to be 1HZ, which combined with the result of 42 MJ results in power production of 42 MW[40]. This is promising to see a significant amount of energy production coming from this reactor concept but it is not definite. First, these are not experimental results, as such the gains are likely to be smaller than this in reality as not every possible energy loss is taken into account. Furthermore, the parameters used in these calculations are not guaranteed in actual operation. For example, $2 \times 10^{20}\text{m}^{-3}$ is the initial plasma density given in the paper,[41] while the initial density is only $4 \times 10^{19}\text{m}^{-3}$ for the prototype reactor currently under construction[42]. While the number given for the prototype reactor is definitely achievable with the current plasma injectors, it will be difficult to achieve the initial density proposed by Laberge.

Assuming that density could be reached, 42 MW could be achieved as long as other losses are kept at insignificant levels. Specifically, the losses due to the wall are still not understood fully. Although the mechanisms by which losses would occur are mostly known there will not be complete data on the actual

[38] Laberge, "Magnetized Target Fusion with a Spherical Tokamak".
[39] Suponitsky et al., "Pressure Wave in Liquid Generated by Pneumatic Pistons and Its Interaction with a Free Surface".
[40] Laberge, "Magnetized Target Fusion with a Spherical Tokamak".
[41] Laberge, "Magnetized Target Fusion with a Spherical Tokamak".
[42] O'Shea et al., "Magnetized Target Fusion at General Fusion: An Overview".

losses which occur until the prototype plant is completed. As such it is difficult to say how problematic the interactions between the wall and the plasma will be and if any of the other challenges discussed will introduce significant losses. This energy yield could be increased by increasing the reactor size or by increasing the percentage of energy recovered from compression. The latter also could result in lower yield if the assumed value of 80% is found not to realistic. As no rationale was included in the paper as to why the 80% number was chosen it not possible to determine its validity.

The other assumption made by these estimates is that the plasma will maintain stability throughout the compression process. While this is by no means a settled subject, the simulated results General Fusion has produced so far indicate that there are likely stable paths through compression. Those paths however, rely on specific initial conditions which must be achieved. This seems to be possible, but difficult, and generally the more difficult a problem is the more expensive it is to solve which reduces the commercial viability of the reactor. Another major concern for the commercial viability is the vaporization of the wall. Aside from the concerns of this effecting the plasma, the material lost must be replaced. If the rate of material loss is too high the cost to replace it could be significant compared to the value of the energy yield. At this point, the rate at which this would occur is not well known. The prototype reactor will hopefully provide data which will remove this concern. However, it may be impossible to eliminate this concern entirely which will make it much harder to achieve viability.

Overall, this fusion reactor concept seems to be scientifically viable. That is, with the required research and development such that plasma and instability and other issues are solved, the reactor will produce net energy repeatably. However the economic viability of this concept is much less certain. The costs to actually build this reactor are currently unknown, however the design does offer some advantages economically over other reactors mainly in the lack of expensive superconducting magnets and pulsed power systems. Specifically, the pulsed power systems in other fusion plants would cost $\sim$ \$300 million while the piston system which acheives the same purpose costs only $\sim \$500,000$.[43] That being said, the only large scale reactor for comparison is ITER which will produce 500 MW and has cost at least 15 Billion USD[44]. Any device produced by General Fusion would be cheaper than ITER but clearly just being cheaper than other fusion reactors does not mean the reactor will be cheap enough as current prices are astronomical. The complex systems involved in maintaining the wall, preparing and injecting plasma, and compressing the plasma will be expensive for the final reactor. This expense, contrasted with the small gain given by this concept, means General Fusion has a lot of work ahead of them to achieve commercial viability.

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