

EVALUATION OF POTENTIAL DESIGNS FOR HIGH PERFORMANCE FUSION ENERGY TECHNOLOGIES

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Abstract- The purpose of this paper is to evaluate a variety of current Hot Fusion technologies that have either accumulated a significant amount of research and experimental data to be justifiably selected as a potential fusion device, or have exceptional theoretical breakthroughs behind their ideas to justify a design for future developmental work. Using KPI's, and Larson's Hot Fusion Criteria, each selected design will be reviewed and scored relative to their key performance indicators and capacity to meet the triple product parametric requirements needed in order to achieve ignition. This obvious method of evaluation has not been attempted before, and will indeed shed some objective insights on the real performance of these current approaches, without the clouded bias of those supporting particular technologies through personal preference. Engineering aspects and the key performance indicators of each device will also be provided so that both the experts and the novices to the field of Hot Fusion can compare and make their own conclusions.

Keywords: Fusion Energy Technology Assessment; Fusion Reactor Design Evaluation; KPI Modeling; Clean Energy Technologies

1. INTRODUCTION

A large variety of plasma devices intended for Fusion exist in the research and development field, however, the majority of them experience the issues of maintaining stable plasma, preventing meltdowns of crucial components, harnessing the fusion energy efficiently, preserving vacuum, and scaling down to an inexpensive configuration. As a whole, most of the Fusion devices that are currently under investigation are nowhere near the size of an internal combustion engine that belongs to a standard family car. Also, the power output from these current devices may exceed the power rating from the mentioned internal combustion engine, though, the yield is almost instantaneous and does not compare on a per volume basis [1]. For these reasons, it may appear that the pursuit of perfecting Hot Fusion reactors is futile, research efforts have been conducted for over sixty years and there are still no commercial outcomes that would compete with the oil and gas industry.

2. FUNCTIONAL MODELLING

The fusion devices are created based on the interrelationships of plasma phenomena conditions. A functional model in Figure 2 is a representation of a hypothetical fusion device. The heating source raises the plasma temperature to the desired temperature [2]. The temperature sensor is used to check the temperature of the reaction point and a controller will be necessary to control the reaction. The Y terms in Figure 2 represent the changes in temperature, coulomb forces, mass flow rate, inter particle distance (cross-section), and the plasma density.

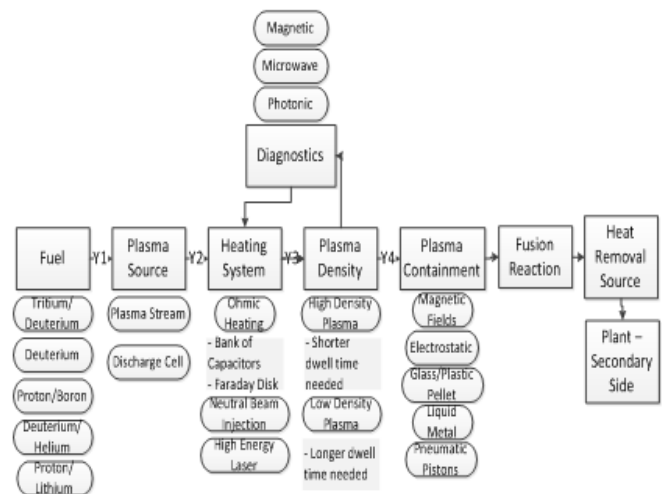


Figure 1. Hypothetical fusion device functional model

3. LITERATURE REVIEW

In today's pursuit of scientific research, a multitude of academic and independent research facilities around the world exist to strive and develop the solution to Hot Fusion technology. Currently, there are two primary approaches identified and pursued by the international community which hold much promise to bare fruitful result, the first is the Magnetically Assisted Confinement approach, which is largely of interest due to their ability to confine Plasma and potentially harness its energy by magnetic coupling, and the second is the Inertial Confinement approach, which seeks to aggressively compress fuel targets in a short span of time, yielding small energy bursts from the Fusion taking

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place. Examples of Magnetically Assisted Confinement devices include the Tokamak, Stellarator, Spheromak, Reverse Field Pinch Devices, Spheroidal Plasmas, Magnetic Mirrors, Θ -Pinches, Z-Pinch, Θ Z-Pinch Combinations, and Field-Reversed Configurations. Examples of Inertial Confinement devices include NIF and Electrostatic Confinement Fusors. The descriptions below include the corresponding advantages, as well as technical issues of the listed fusion devices.

3.1 Tokamaks

The Tokamak uses a strong magnetic field to confine the plasma in a toroidal chamber. The plasma torus is regarded as a single secondary winding of a transformer. A current flowing in the primary transformer winding induces a plasma current in the secondary single loop plasma (the toroidal chamber). The toroidal magnetic field alone is not sufficient to establish a plasma equilibrium. In order to achieve equilibrium in Tokamaks, where the plasma pressure is balanced by the magnetic forces, it is necessary to have a poloidal magnetic field. This field is produced by the plasma current flowing in the toroidal direction. The superposition of the toroidal field B_ϕ and the poloidal field B_θ produces magnetic field lines that move around the torus in a helical trajectory. The toroidal field travels around the torus in circles, whereas the poloidal field travels in circles orthogonal to the toroidal field. Tokamak plasmas are initially formed by the Ohmic heating which is also used for the current ramp-up and quasi-steady current phase. The modern Tokamaks also use other supplementary heating methods, such as the neutral beam injection (NBI) and the radio frequency (RF) heating, to increase the plasma temperatures to ignition temperatures [3].

The primary advantages of the Tokamak design are that it uses a transformer to generate plasma instead of electrodes (no electrode erosion means less impurities in plasma). Also, the helical field of Tokamaks eliminates particle drifts caused by field curvature and gradient, and the torus shape doesn't lead to end losses, since, the magnetic field lines circle around the torus and close on themselves [4].

The technical issues, on other hand, include the fact that Tokamak operates only in a pulsed fashion (due to transformer saturation) and it suffers from current-driven and pressure-driven instabilities as a result of the toroidal plasma current and pressure gradient. In fact, it is vulnerable to other MHD instabilities such as edge localized modes (ELMs), eddy currents, and tearing modes, which have a multitude of destabilizing effects on plasma (e.g. degradation of particle and energy confinement, thermal stress on Tokamak wall...etc). Another technical constraint is the manufacturing and the assembly of the coil systems that may cause asymmetries in magnetic fields, called error fields, which can create mode locking of plasma torus [5].

3.2 Stellarators

A Stellarator is similar to a Tokamak in that they both utilize the torus shape. Unlike the Tokamak, however, the Stellarator has a helically symmetric torus that uses an external coil system to generate a large axisymmetric toroidal field, a moderately sized helical field with $l\theta-n\phi$ symmetry, and a small axisymmetric vertical field. The toroidal current in the Stellarator is driven by the bootstrap effect so there is

no Ohmic or externally driven currents [6]. The advantages of such a design are that the plasma operation is steady-state due to the absence of Ohmic current and other current drives. Also, there is no toroidal plasma currents, which means that there is no current-driven instabilities [7].

Despite the positive aspects of the Stellarator, the technical disadvantages still exist. For instance, the coil system required to generate the Stellarator magnetic field is quite complex, and requires a strong supporting structure because of the curved magnetic coils producing large forces. Furthermore, it is difficult to make compact Stellarator devices as well as model their plasma and magnetic fields in the device, due to the complex geometry involved [8].

3.2 Spherical Torus

A Spherical Torus (ST) is the low aspect ratio limit of the conventional Tokamak design (aspect ratio $A = R/a$ is the ratio of the major to minor radii of the torus). The ST approach minimizes the size of a Tokamak power core by discarding components from the inner side of the plasma such as the inboard blanket or shield, inboard poloidal coil systems, and Ohmic heating solenoid [9]. The D-shaped plasma cross-section and the low aspect ratio of ST provide strong intrinsic plasma shaping and enhanced stabilizing magnetic field line curvature [10]. It is an advantageous design due to its practicality, and simple to build compact size. Also, the ST design has lower magnetic field requirements and can use non-superconducting magnets to generate magnetic fields. The classical kink instabilities and higher-order ballooning modes are strongly suppressed due to the low aspect ratio, and correspondingly the ST design is capable of operating at high beta values (ratio of plasma pressure to the magnetic pressure) [11].

However, ST designs face the lower plasma pressure in spite of higher beta, because the magnetic field drastically changes across the plasma volume. Although the ST design does not require the superconducting magnets, having them to generate strong magnetic fields for the control and limitation of the plasma pressure would be beneficial, although difficult to do, due to the small ST center. Also, the ST operation requires more secondary heating systems to drive very high toroidal currents and to maintain the plasma. It is possible to drive the toroidal current using only the bootstrap effect, but this idea is still under investigation [12].

3.3 Reverse Field Pinch (RFP) Devices

RFP is an axisymmetric toroidal confinement configuration similar to Tokamak but with very different current density and magnetic field profiles. RFP, like the Tokamak, uses both toroidal field B_ϕ and poloidal field B_θ to confine the plasma. The poloidal field is generated by the plasma current, whereas the toroidal field is generated by both the plasma current and by external coils. The RFP plasma is stabilized using a strong magnetic field shear produced by the radially varying (and decreasing) toroidal magnetic field. The toroidal magnetic field at the edge is oppositely directed to the toroidal field on axis. RFP is characterized by a low safety factor ($q < 1$) with comparable magnetic fields in poloidal and toroidal directions [13]. The primary advantage of such design is that there is practically no beta limit, the plasma can be produced entirely through

Ohmic heating, and the superconducting magnets are not required due to lower magnetic fields. Also, RFP designs are fairly resilient against high energy neutrons, since it uses a close-fitting conducting shell to stabilize non-resonant kink modes [14].

Unfortunately, due to the low safety factor q , RFPs are also subject to higher levels of MHD instabilities which affect confinement, there are also large radial transports from magnetic fluctuations, as well as large driven currents that cannot be achieved by Ohmic heating alone nor the bootstrap effect due to physical limitations, which are required to maintain the field equilibrium. Also, even though the conducting shell is advantageous to have for preventing the non-resonant kink modes, there is the growth of resistive wall modes due to this shell [15].

3.4 Spheromak

A Spheromak is a compact, axisymmetric, toroidal configuration where the magnetic field is produced almost entirely by currents flowing in the plasma. The Spheromak is confined through the self-induced field that follows a helical path. The internal currents are nearly parallel to magnetic fields so that the forces within the spheroid are in an equilibrium state. The Spheromak has a toroidal field nearly equal to the poloidal field. There is no linkage between the SP and external coils since the toroidal field of such configuration vanishes at the boundary (i.e. the wall). The Spheromak can be generated using a coaxial source that consists of a pair of cylindrical electrodes, one inside the other. A working gas is injected between the electrodes and ionized to form a plasma which is frozen in the initial magnetic field produced by the inner electrode. The Lorentz force induced by the original field and the currents flowing in the plasma pushes the plasma away from the coaxial source into a flux conserver. The fields between the source and the plasma reconnect to form an isolated Spheromak. The Spheromak can also be produced using a variety of methods like flux-core induction, combined theta-pinch and z-pinch, helical injection from a coaxial, magnetized gun, a conical θ -pinch, and a kinked z-pinch. The uniqueness and advantage of the Spheromak is that they require small power input, there is no need for external magnets, since the SP's are confined by their own magnetic fields, and the steady state operation of Spheromak's is realistic without excessive expenditures. Even without the external magnetic fields, the Spheromak's experience long confinement time, and it makes them a feasible option for fueling other plasma devices (e.g. Tokamak).

Despite all their advantages, Spheromak's however, have a complex behavior, that is, their dynamics are hard to predict and control. The dynamo effect induced by the Spheromak produces fluctuations and turbulence, as a result, Spheromak's are vulnerable to tilt, shift current and pressure-driven instabilities. Also, Spheromak's are subject to external forces due to the thermal gradient between the plasma and the cold surroundings which can cause energy loss, especially in environments where convective heat transfer effects take precedence, and, Spheromak's have low beta levels as a result of the Mercier limit [17].

3.5 Magnetic Mirrors

A magnetic mirror system is a plasma confinement device that uses magnetic coils to create a strong magnetic field at the end tips of linearly restricted plasma. The combination of two magnetic mirrors forms a magnetic bottle where the ions are reflected towards the internal linear plasma flux [1]. It is an advantageous design in that high confinement times can be achieved given that the magnetic mirrors are sufficiently powerful. Also, the plasma is magnetically confined to a space where the particle collisions are continuously occurring until the energetic threshold. Some recent investigation encourage a multi mirror reactor that may offer a possibility of having a high beta, especially in hybrid devices [18].

For some time it was hoped that the magnetic mirror idea would yield results for fusion confinement, but when the high axial end losses could not be mitigated it became more of a historical curiosity. In order to have reasonable confinement in magnetic mirror devices, the current facilities have to be fairly large and complex. The complexity of calibrating the magnetic mirrors may result in MHD instabilities if done incorrectly, or if the coils have flaws. The major MHD instabilities that have a high potential of occurring in these devices are the interchange instabilities, that is, the plasma at the mirror is usually denser than the plasma confined in the central section. As a result the plasmas may experience unstable modes such as drift cyclotron loss cone, mirror, Alfvén ion cyclotron, convective loss, and ballooning [1].

3.6 Θ -Pinches

Θ -Pinch enacts cylindrical confinement of plasma by the use of a current carrying sheet wrapped around the plasma body. Plasma is radially compressed via the instantaneous axial field B_z that induces a current in plasma in the θ direction. The coil currents can provide uniform confinement and suppress instabilities, and the generation of plasma does not have to be via the electric discharge [1]. Despite being a convenient device to radially compress the plasma to the fusion conditions, the dimensional and energy expenditures are quite large (kilometer long devices) and questionable in terms of realism. Also, the coil in the device is pulsed, which puts up some control barriers for continuous fusion. The current carrying sheet idea is not necessarily realistic on its own, but it is possible to apply it in hybrid machines [19]. The technical issue of rapid plasma losses at end-tips (particle drifts), may require a long current-carrying sheet or alternative design approaches to either putting magnetic mirrors, plugging or curving the ends, which result in significant heat losses, and MHD instabilities. There is also the charge distribution in the sheet, that has to exceed the charge carried by the plasma or else the instabilities will become dominant. Lastly, the Θ -Pinch devices have the magnetic lines of force elongated azimuthally in the direction of the current flow which creates significant plasma distortions [20].

3.7 Z-Pinch

A Z-pinch device is composed of an anode and a cathode as two concentric cylinders. The anode has a flat end-tip surface and the cathode is a tube enclosing the anode. Z-pinch occurs as a result of high current discharge from a capacitor bank and into the anode cathode configuration. As a result of

current discharge the plasma is formed inside the inter-cylinder space, and, as current continues to dissipate, the plasma is propagated towards the tip of the assembly due to increasing magnetic field. This plowshare-like propagation of plasma is concluded at the tip of the device, where the dense plasma sheath collapses onto a lower density plasma, thereby enacting the effects of Alfvén waves and Ohmic heating. The established plasma pinch lasts microseconds, at best, and during its formation resembles a vortex centered at the tip of the anode. Z-pinch is an unstable method of achieving potential fusion, although, due to the instabilities, it has a high capacity to produce high neutron yields at high currents [21]. The high-density plasma formation at the anode tip is not very well described by the conventional Magneto-Hydro-Dynamic equations, hence the parallel application of the Monte-Carlo Method is often used to model neutron yields. Z-pinch has the advantage of being a fairly small device that can generate very high density plasmas, and it finds itself useful generating soft x-rays and neutrons [22]. Unfortunately, Z-pinches only work in pulsed manner due to instantaneous discharge of the capacitor banks. The use of electrodes results in gradual wear and consequential contamination of plasma with impurities that make it extremely difficult to achieve fusion. Also, the end-losses and current-driven Rayleigh-Taylor instabilities at the anode tip (Sausage-Instabilities) are prevalent in Z-pinch machines. On the construction side, it was observed that in the metal walled Z-pinch machines there is a strong cathode-to-anode asymmetry of the discharge, and the appearance of current leaks near insulators may be possible during pinch formations [1].

3.8 Θ Z-Pinch Combinations

A variation of geometrical alternation in the orientation of the plasma discharge surfaces and the magnetic coil setting a range of different Z θ -Pinch designs is possible. Hard-core, Screw, and Belt Pinches utilize the z-pinch effect to compress plasma radially via the self-induced currents, and the use of inducting magnetic coils is for confining and stabilizing plasma against kink instabilities. Due to the combinational effect of the two pinches the helical shape of the pinch is similar to Tokamak plasma profile. Unlike the Tokamak however, the stability yields about twice the β , that is, the plasma magnetic confinement is better in terms of maintaining plasma at a steady pressure [1]. Among other devices it is justifiable to present this hybrid device on its own, because of its ability to out-perform the composing devices due to its ability to be made work continuously, and maintain high stability of plasma [23]. However, some technical issues are transferrable from the composing devices. The electrodes may lead to plasma contamination due to material wear (unless electrode-less plasma induction is used), and the end losses with the escape of high energy ions occurs unless the ends of the device are secured with magnetic mirrors or metallic plugs. Although the Z θ -Pinch devices can be made fairly compact, the issue pertaining to the complex manufacturing still remains aloft. Also, depending on the arrangement of coils and discharge elements the error fields and the tearing modes may take precedence [24].

3.9 Field-Reversed Configurations

A field reversed configuration (FRC) is a compact toroid configuration that contains no toroidal field. The magnetic topology of FRC is similar to an elongated, low aspect ratio, toroidal θ -pinch. The FRC plasma is confined by the poloidal magnetic field generated by plasma itself. FRC plasma is traditionally formed by the field-reversed θ -pinch (FRTP) method. The FRC plasma is formed inside a discharge tube filled with a working gas. The formation process starts with applying an axial bias field produced by a cylindrical one-turn coil. The inductive discharge generates a pre-ionized gas which freezes in the bias field. Afterwards, the main axial field is reversed and a magnetic reconnection occurs between the main field and the bias field, forming a closed magnetic structure. Finally, the FRC plasma is compressed and heated by further increasing the main field. Other FRC formation methods have been introduced such as Counter-Helical Spheromak Merging (CHSM), Rotating Magnetic Field (RMF), and Field-Reversed Mirror Configuration (FRM) driven by Neutral Beam Injection (NBI), Relativistic Electron Beam (REB), and Intense Light Ion Beam (ILIB) injections [25]. There is a significant interest in the FRC devices because they are easy to build, small, and have a very high beta value ($\sim 100\%$). Since the FRC does not have a central electrode, there is no toroidal magnetic field and no rotational transform, hence, the resulting topology is fairly simple structurally as well as magnetically. Some FRCs can be used for fuelling the hybrid fusion reactors, but due to the high power density they are expected to yield some fusion products during collisions between FRCs alone (given the right confinement) [26].

The advantages of FRCs are quite appealing to motivate some investigators to dwell further. The technical issues, however, are also worthwhile to consider. For instance the FRCs are vulnerable to rotational instabilities, which can be suppressed by applying a multipolar field by external coils with straight or helical windings. However, if the suppression field is excessive it may engage in tearing modes during the formation phase of FRC. Also, FRCs are vulnerable to tilt and shift instabilities, and turbulent transport. In order to sustain the FRCs for long time it may be required to employ additional methods like Neutral Beam Injection (NBI), and Radial Magnetic Field (RMF). At current date, there is no quantitative agreement between experimental results on FRC stability and theoretical analyses, which complicates the prediction of the results of any future FRC experiments [27].

3.10 Inertial Confinement Devices (ICDs)

In ICD, the fuel is compressed and heated extremely fast so it reaches fusion conditions and is burnt before it can escape. The fuel is in solid pellet form and contains few milligrams of a Deuterium and Tritium mixture. Hundreds of high-energy laser beams are shot at the sphere resulting in an explosion of the shell. Due to the opposite inertial reactions the rest of the shell flies inward creating thermonuclear conditions for the gaseous mixture. The imploding materials inertia then gives leeway for the fusion to occur during the short period of time which the plasma is kept together.

There are two methods for performing laser implosion, the direct drive and the indirect drive. With the indirect drive method the laser is focused from outside through holes onto the interior surfaces of this cavity rather than directly onto the capsule resulting in an evaporation of the inner surface of the cavity and causing a dense metal plasma to form. The laser energy is converted to X-rays and bounces around many times rather than hitting the target directly and strikes it from all directions penetrating the capsule from all sides uniformly. On the other hand the direct drive method directly fires on to the capsule [1]. To date, the ICDs have actually achieved a record in sustained fusion of deuterium and tritium on the order of tens of milliseconds. In order for this fusion reaction to generate more energy than consumed, however, the plasma must be extremely dense where it is 1000 times denser than a solid. This raises issues in the ability to store and deliver such a high energy onto a tiny target as well as the time required to change the target after each pulse. This brings the technical issues of ICDs such as its operation in a pulsed fashion due to the need to replace the fuel pellets. The fuel pellets have to be perfectly spherical or else the fusion will not take place, which adds to manufacturing costs. Also, extremely large facilities and floor space is required to operate the lasers and to achieve relatively small burst of instantaneous energy, the economic aspect does not make ICDs a feasible option to generate energy, and it is neither scalable to miniaturization at the present moment [28].

3.11 Electrostatic Confinement Fusors

The Hirsch–Farnsworth Fusor is an ion accelerator that contains an outer vacuum container, filled with fusion gas, with a negatively charged spherical inner grid. The negative high voltage is applied to the inner grid at the low plasma pressure to get Paschen arc. Near the low-pressure end of the Paschen arc region with voltages of tens of kilovolts or higher, the accretion of ions is formed in the center of the Fusor's inner grid; this region is where the fusion between particles is intended to occur. The main idea is that fusion is driven by particle velocity, not the plasma heating. The ultimate goal is to conserve ions at the center of the device so eventually all the ions fuse.[29] The Elmore-Tuck-Watson machine was the improvement of Hirsch–Farnsworth's Fusor by having the inner grid positively charged, thus attracting the electrons [1]. At high voltage the electron will pass through the intermittent grid, and ions at high energy will pass through to the central region to produce fusion. Such a device is capable of producing small bursts of neutrons, and can be miniaturized to produce small amounts of fusion by-products [30]. However, the amount of technical issues involved makes the Fusor not very appealing for producing steady fusion reactions, despite its scalability. To date, there has not been a case where self-sustaining fusion occurred in a Fusor due to the pulsed and unstable nature of its operation. The grids are an obstacle to the energetic ions and may become evaporated over the course of the device operation, thereby contaminating the plasma. Also, a wide variety of losses such as ion thermalization, scattering, bremsstrahlung radiation, electron cusp, acoustic-wave compression of the core, and the counter-streaming instabilities at the center of the reaction occur in Fusors. Lastly, the confined plasma can

be brought together to only such extent that only minimal amount of reactions occur[31].

3.12 Polywells

A Polywell device is a cube shaped magnetic cusp electron trap that creates a virtual cathode in the center to achieve Fusion via Inertial Electrostatic Confinement. Unlike the Fusor device that relies on multiple electrostatically charged grids, the Polywell relies on accretion of electrons at the center of device and the consequential tugging of protons into the potential well. Over the course of generation of the virtual cathode, the magnetic field also confines plasma to a limited region of operation, unlike the Fusor, the energetic particles maintain about a limited region of space [32]. The advantageous aspect of a well-made Polywell device is that plasma is compressed spherically and the ions do not collide with any metallic grid; hence, there is no consequential thermal energy loss. Another advantage of the Polywell is the possibility of operating in a continuous fashion via the existence of the virtual cathode. Due to the continuous operation, the plasma heating can be achieved via the RF signals and the fuel contamination from metals can be avoided. Ideally, the particles drift along the magnetic field lines and could be confined in the center given a strong enough magnetic field, and, if needed, the auxiliary plasma injection can be used via the ion injection or spheroid plasma injection [1].

The beta of these devices is low due to the current limitations in magnetic devices, and it requires a unique balance of magnetic and electric fields in order to create a stable virtual cathode. Furthermore, the end-losses due to the leaks of high energy ions, make the confinement time be an fragile balance between electric currents applied to virtual cathode generator and the injection energy. Hence, either a larger or more current demanding device is needed to avoid power losses, or the consequential price is the drop in performance due to increase in potential well [31]. Unlike the Fusor, which could be scaled to suit the demanded needs, a scaling law for the virtual cathode (electron confinement) is only applicable when electron critical flux is inside the device radius. The device geometry is critical to have a stable plasma configuration [1].

4. HPFR Parameter Evaluation

In this particular section, the evaluation of the critical parameters for the high performance Hot Fusion reactors are justified through the analysis of key performance indicators (KPI), and the capacity for each device to achieve the Larson's Hot Fusion Criteria . The current Fusion research facilities around the world are thoroughly involved in understanding Plasma properties, thus it is not easy to facilitate the superiority of one technology over the other, since all of them are largely research oriented. Nonetheless, it is still possible to present what the researchers have highlighted to be the milestones in achieving commercial Fusion and compare that data accordingly.

To mitigate the involved discussion of physics and to gain perspective on the various devices, it is convenient to start with the KPI analysis as a starting point. Three KPI branches were identified as the economic indicator, which will highlight initial costs, operational costs, maintenance costs,

design flexibility, adaptability, and manageability, the conservation indicator, which will focus on the life cycle, material use, durability, waste generation, safety, and the quality of the fusion device, which takes into consideration the size, the complexity (ie. Number of parts), confinement geometry, and commercial cohesiveness. By covering these KPIs it is expected that the reader will benefit from a perspective on the current status of each fusion device from a more holistic sense.

4.1 Evaluation and Comparison for Existing HPFR Designs using KPIs

The evaluation of current Fusion devices based on KPIs is fairly uneasy, and requires a lot of detective work and accounting based labor. Spending and costs are hard to track without access to the key proposals and accounting documents originally compiled by the design. However, the base figures were found as a range for specific parameters with respect to the base-line values, and thus a range will be provided for the indicators in each of the four KPI branches. The design flexibility of the Fusion device is ranked on a 1 to 8 basis in regards to how well the device can adapt to the change of external power regulation and cooling components (1), alternations of the design in terms of additional diagnostics equipment that can be attached (2), dimensional alternations that can be performed via the actuators and diverters inside the reactor chamber (3), flexibility to the addition of multiple plasma sources (4), the possible alternation of plasma facing components to adjust for commercialization (5), implementation of the energy harvesting techniques on the current devices (6), simplification of the design to less than 10'000 parts (7), and lack of the exotic/toxic materials (8). The device adaptability is ranked from 1 to 8, with 1 being the most adaptive to the economy and 8 indicating lack of adaptability. This ranking is based on how many institutions are actively involved in the research of a particular device, how much is invested, what is the public and academic involvement, as well as the relevant literature outlining the commercial design advantages. Manageability is simply the minimum number of people that are directly involved in the project for its operation on site [33,34,35,36,37,38,39,40,41,42,43,44,45].

The next KPI is the conservation indicator for the different Fusion devices and it includes the life cycle, material use, durability, waste generation, and safety. The lifecycle of the devices is presented as the approximate number of years that a Fusion device has been in operation before any major or significant updates. It is worthwhile noting that the durability of any of the Fusion devices, described thus far, depends highly on the materials chosen. From the table below it becomes evident that most of the materials that are involved in the reactor design are metallic and hence can withstand high stresses and thermal expansion. However, the ability of the metals to sustain a highly confined vacuum under the standard atmospheric conditions is part of the problem. Making sure that the vacuum is pure and contamination does not take place within the Fusion reactor is vital.

Table 1. The economic indicators for the current fusion technologies.

Device	Initial Costs (\$)	Annual Operational Costs (\$)	Annual Maintenance Costs (\$)	Design Flexibility	Adaptability	Manageability (min# of personnel)
Tokamak	100K to 16.6bn	8M to ~44M	6M to ~32M	1,~2,3,~4,5,~6	~1	20-200
Stellarator	3.4K to 1.28B	1K to ~3M	1K for small experiments and for large 200M to ~600M	1,~2,3,~4,~5	~1	1-200
Spheroidal Torus	10K to ~1M	3M to 40M	5.5M to 26M	1,2,~3,4,~5,~6,7	2	10-20
Reverse Field Pinch Device	~1M and up	~3M to ~40M	5M to 6M	1,~2,~3,~4,5,~6	~2	10-50
Spheromak	10K to ~1M	7.4M to 9.4M	5M to 6M	1,2,3,7,~8	~4	~10-~100
Magnetic Mirrors	10K to ~372M	~10K to ~100K	~10K to ~100K	1,2,~4,7,8	7	5-20
Ø-Pinch	10K to ~1M	~10K	~10K to ~100K	1,2,~4,7,8	8	1-10
Z-Pinch*	10K to ~1M	~10K to ~100K	~10K to ~100K	1,2,3,~4,~5,~6,7,8	3	1-10
ØZ-Pinch	~10K	~10K	~10K	1,2,3,~4,~5,~6,7,8	6	1-10
Field Reversed Configuration	100K to ~200M	~10K to ~100K	~10K to ~100K	1,~2,3,4,3,6	~2	10-100
Inertial Confinement Devices	1XK to ~1XM	~1XK to ~1XM	~1XK to ~1XM	~1,2,~4	4	100-600
Electrostatic Confinement Fusors*	1K to ~1M	1K to 100K	1K to 100K	1,2,~4,~6,7,8	~5	1-10
Polywell	100K to ~1XM	1XK to 100K	1XK to 100K	1,2,4,~5,7,8	~5	1-10

Note: tilde indicates close proximity but does not make the device reach the target value

*Z-pinch and the Fusors find some use in neutron generation, hence the ~6 in design flexibility

Factors like cleanliness and purification systems are included to highlight the importance of excellent house-keeping when it comes to the dually sensitive and powerful Fusion machines.

Table 2. The conservation indicators for the current fusion technologies

Device	Life Cycle (years)	Material Choice	Durability	Waste Generation	Safety Factors
Tokamak	4-20	Stainless Steel	In general, a high level of durability is chosen on the merits of thermal expansion and stress robustness. Clean and purification enabled. Maintenance of the internal components is only done in clean suits and as rare as deemed possible, diagnostics and injectors change /cleaning Chamber external work requires meticulous electrical and mechanical maintenance.	Neutrons can cause radiation damage to the shielding, which may result in slightly radioactive materials for as long as 30 to 40 years, depending on the regulation policies. End of life components require recycling or are simply dumped as waste; note the exotic/toxic materials. Maintenance and overhead waste.	Leaks. Plasma Instabilities. Toxic material containment breach. Rarefied pure vacuum conditions. Power breach. Cooling breach. Neutrons. X-Rays. Audible Noise. EM interference. Vessel breach/implosion. Excess Heat Losses.
Stellarator	2-20	Copper			
Spherical Torus	2-20	Carbon Tungsten			
RFP	2-20	Titanium			
Spheromak	2-20	Niobium			
Magnetic Mirrors	2-20	Liquid Nitrogen Superconducting Materials			
Ø-Pinch	2-20	Hydrogen			
Z-Pinch	2-20	Deuterium			
ØZ-Pinch	Unknown	Tritium			
FRC	2-20	Helium Isotopes			
ICD	10-30	Boron			
ECF	2-10	Rare Metals			
Polywell	2-10	Semiconductors			
		Synthetic Oils Coolants Typically, fractional amounts of hazardous, toxic, or exotic materials			

The final KPI is the quality of the fusion device, which again takes into consideration the size, the complexity (i.e. Number of parts), confinement geometry, and commercial cohesiveness.

Table 3. The quality indicators for the current Fusion technologies

Device	Size Area [m ²]	Complexity # of parts	Confinement Geometry	Commercial Cohesiveness
Tokamak	0.8-1182	Designs vary, part count is anywhere between 100,000 and up to or beyond the one million parts	Torus, possible employment of the D-shape, bundle, or ergodic diverters, or limiters	Scientific Value/ ITER oriented
Stellarator	1.2-572.5		Twisted Torus	Scientific Value WX oriented
Spherical Torus	2.5-~4		Spherical Torus	Scientific/Commercial
RFP	12.6 and up		Torus Variants	Scientific Value/ ITER oriented
Spheromak	0.8-1	1,000-100,000	Sphere propagating on a line	Scientific Value
Magnetic Mirrors	1-1160	~1,000-100,000	Cylinder	Historical/Scientific Value
Θ-Pinch	Needs to be long to be feasible	~1,000-10,000	Cylinder, Torus Variants	Historical/Scientific Value
Z-Pinch	0.04-0.2	~1,000-10,000	Cylinder	Neutron Generators
ΘZ-Pinch	Unknown	~1,000-100,000	Cylinder	Scientific Value
Field Reversed Configuration	10-80	10,000-100,000	Sphere propagating on a line	Scientific Value Active Commercial Research
Inertial Confinement Devices	0.75km ²	100,000 to beyond 1 million	Sphere/miniature cylinder/hohlraum	Weapons Research High Energy Science
Electrostatic Confinement Fusors	1-4	1,000-10,000	Sphere	Hobbyists, Neutron Generators, Historical/Scientific Value
Polywell	1-25	10,000-100,000	Sphere	Scientific Value

5. DISCUSSION AND FUTURE WORK

Considering the results found above, we can see that the top five reactors which scored the closest to achieving Larson’s criteria for D-T fusion are the Reversed Field Pinch, the Spherical Torus, the Tokamak, the Stellarator and the Spheromak in the respective order of first to fifth. These five devices all share two things in common, one is the geometry that they operate with, the torus, and the other is the method of confinement, which is the magnetic approach. Even though the RFP operates in a torus like shape, its approach of achieving fusion varies slightly from the other 4 in that it uses a magnetic pinch configuration. This can achieve high temperatures and densities, but also low confinement times, relative to the other toroid approaches. Although current research RFP devices haven’t achieved fusion, its performance based on the data suggests that field pinch arrangements paired with torus geometry seems to hold well as a solution to fusion, especially if the pinch can be stabilized for a longer confinement time. Other devices like the Polywell and the Fusor, which achieve theoretical temperatures of 50-80 keV, scored poorly, coming sixth and ninth respectively. This is due to the fact that although they may be able to reach high temperatures, the overall method and configuration lacks the ability to densely store and confine energy. This doesn’t mean that the electrostatic confinement method is obsolete, however, as a road to fusion, the approaches used thus far haven’t performed well, partly because of the lack of research. Inertial Confinement Devices like the one at the NIF scored relatively low as well, mostly because of the small confinement time, but has been recorded to achieve ignition, although not fully sustained. This makes it difficult to actually assess the ICD relative to the other devices, though the approach seems entirely unfeasible when the cost and scale of construction is taken into serious consideration.

It is hoped that anyone who is interested in getting involved with the fusion research understands the risks and costs associated with each specific fusion configuration. It is unlikely that either the Tokamak’s or the Stellarator’s will be possible to miniaturize in the next 20 to 30 years, in order to be feasible in terms of achieving ignition. It is likely that hybrid devices will be the outcome of current fusion research, though the miniaturization of such configurations will be the main goal in the long run. Hence, it would be highly beneficial for scientists and engineers to investigate the miniaturization of the plasma devices, diagnostics, and control options. Investigations in the field of plasmonics, plasma modelling, confinement methodologies, as well as the plasma device design methodologies will play a large role in pushing fusion technologies to the commercial level. Any scientists who are currently working on the nationally supported fusion devices are encouraged to continue pursuing the scientific research for the better understanding of plasma phenomena; it is advisable, however, to keep in mind engineering limitations and the financial constraints. The value of the fusion energy developments for the benefit of humanity is immense, and will be a historical milestone when it is made available as current coal power-plants. This makes it an attractive goal for the national and international communities, as well as private investors seeking to make a historical discovery. Nonetheless, achieving this goal is a

4.2 Evaluation and Comparison for Existing HPFR Designs using Larson’s Hot Fusion Criteria

In order to be able to objectively assess and compare all these different hot fusion devices, it is necessary to assess the capacity of each device relative to its ability to achieve sustained fusion, or ignition. Using Larson’s Hot Fusion Criteria for D-T reactions, which states $n_{20} * T_k * \tau_E > 6.0 * 10^{21} keV * \frac{Particles}{m^3} * s$, each fusion device will have its specific parameters of temperature, density and confinement time form a product which will score relative to the basic minimum of what the criteria requires. This method assumes the most practical and objective approach available to truly assess the many different kinds of fusion devices, regardless of the design’s personal unique parameters and methods of function.

Table 4. The comparison of each device’s capacity to meet Larson’s Hot Fusion Criteria

Device	Temperature [keV]	Density ρ _p [particles/m ³]	Confinement Time [mS]	Total Score $\frac{x}{6 * 10^{21}}$	Ranking
Tokamak	1.5	1.5E+20	0.05	0.001875	3
Stellarator	1	5E+19	0.035	0.000292	4
Spherical Torus	4	1E+20	0.67	0.044667	2
RFP	20	9E+20	0.05	0.15	1
Spheromak	0.4	5E+20	0.0005	1.67E-05	5
Magnetic Mirrors	0.06	2.7E+18	0.0025	6.75E-08	7
Θ-Pinch	1	4E+16	0.0015	1E-08	9
FRC	3	5E+9	0.01	2.5E-14	10
ICD	10	1E+20	1.101E-07	1.84E-08	8
ECF	80	1E+16	0.02	2.67E-06	6
Polywell	50	2E+14	4.40788E-07	7.35E-13	9

[65][66][67][68][69][70][71][72]*Note: Some data has discrepancy based on the existing documentation and/or complexity of the measurements

matter of making correct decisions for the investment of time, energy, and money to a specific fusion technology.

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