Affordable Electrostatic Confinement Device

A Cheap, Affordable Future for Fusion

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Daniel Liu

Johnson Yang

Abstract:

The Affordable Electrostatic Confinement Device (AECD) is a low-cost, environmentally friendly, open-sourced fusion reactor that is licensed under CERN-OHL. Inspired by predecessors such as the Farnsworth-Hirsch Fusor, this device utilizes inertial electrostatic confinement (IEC) to achieve fusion between deuterium nuclei. This demonstrates the potential of fusion to provide clean energy, as nuclear reactions facilitated by IEC do not result in the production of harmful radioisotopes associated with nuclear reactors. While the AECD is not capable of producing net positive energy, it serves as a proof of concept for affordable modular nuclear reactors that could provide underrepresented communities with clean energy.

The AECD features innovative design improvements that effectively reduce the costs and complexities associated with production. A notable improvement is the implementation of an outer grid that is integrated with the vacuum chamber walls. The device also uses a neon sign transformer, a mundane alternative to complicated electrical systems, to provide the high voltages that are necessary for robust electrical fields to be generated.

It is paramount that the AECD is affordable and accessible. However, this also results in the overall capabilities of this device being weaker than those of its counterparts. The AECD cannot generate electrical fields strong enough to accelerate ions to velocities that enable them to overcome the Coulomb Barrier. As a result, the alternative outcome of fusion through quantum tunneling is emphasized. This enables the AECD to conduct fusion, albeit at lower rates.

The main purpose of the AECD is to address the lack of energy security in underrepresented communities, a reality that many rural populations experience.

By providing a low-cost, environmentally friendly fusion device, the AECD aims to empower inaccessible communities with an energy source while also enabling scientific applications such as neutron generation. Although the current version of the AECD faces limitations such as the inability to effectively sustain fusion and provide positive net energy, the AECD is a step in the direction of sustainable energy.

Problem Statement & Justification for Solution:

The most prevalent sources of electricity are largely unsustainable. The combustion of fossil fuels results in more than 35 billion tonnes of CO2 being emitted into the atmosphere, exacerbating global warming. Due to the occasional lack of oxygen, the frequent burning of fossil fuels also cause incomplete combustion quite often. This results in the production of carbon monoxide and soot, which when inhaled, can pose a significant risk of poisoning and death. On the other hand, generating energy through nuclear reactions can be a feasible method for providing power.

Small Modular Reactors (SMRs) are devices that could be versatilely used to provide electricity to small communities. Despite the many new innovations in nuclear energy, the main issue lies in the price. Generally, people are reluctant to invest in new energy solutions as they are not economically advantageous compared to traditional energy sources. In contemporary societies, most people choose not to invest in modular reactors due to their high price per unit of electricity. However, small modular reactors have many merits.

The word *modular* in SMRs (Small Modular Reactor) refers to the ability to create major parts of the nuclear steam supply system. Due to their smaller sizes, application and construction times are significantly reduced compared to traditional nuclear power plants. As a result, it is beneficial as it becomes very flexible in both application and finance. Not only that, but additional modules can also be added if more energy is demanded. Consequently, it is very efficient for energy generation and flexible to changes ("Small Modular Reactors.").

From a community perspective, SMRs are advantageous as they provide people with a sustainable and flexible source of energy. A typical SMR could potentially generate 300 megawatts of electricity, which would be able to power a village or small city. Currently, around 84% of people experiencing energy insecurities live in rural areas (J.M.K.C. Donev et al.). Many of these people cannot enjoy modern amenities, and even if they do not need those amenities, they still struggle with managing their work at night. By implementing SMRs, electricity can become widespread. Not only can they be placed in small cities or rural villages, but they can also be placed in large cities since SMRs can be linked to multiple units as the amount of electricity needed varies. This is imperative as it cuts costs and eliminates the ethical concerns of land usage with conventional nuclear power plants.

Furthermore, SMR technology has the potential to bring clean, low-cost energy. As the fusion reaction can be replicated and no long-term radioactive wastes are released, customers could save money while also reducing emissions. Thus, the application of SMRs can benefit producers, consumers of various demographics, and the environment ("Small Modular Reactors.").

Safety Considerations:

The AECD is a device that requires high voltages to function. In this design, the outer grid of the reactor is exposed. Correspondingly, the vacuum chamber should be considered as a potential hazard. When functioning, the neon sign transformer will output AC electricity of up to 15kV. If not operated properly, it may lead to a fatal shock. According to the National Institution of Standards and Technology, devices of similar capabilities must be operated by two or more people (NIST). Moreover, the operators must be protected with personal protective equipment (PPE) rated for high voltages. The voltage levels involved are considered extremely high, and according to relevant regulations, there must be an enclosure dedicated to the application. During operation, personnel should stay at least 1 meter away from the chamber.

Inertial Electrostatic Confinement (IEC) Fusion:

The AECD uses inertial electrostatic confinement (IEC) to achieve fusion. In these reactors, there are two grids with a high potential difference. The electric field strength between these grids is given by the equation:

$$E = \frac{v}{d}$$

E is the field strength ($\frac{N}{C}$)

v is the potential difference (v)

d is the distance between the grids (m)

In the presence of an electric field, charged objects will be accelerated, which gives the following equation:

$$E = \frac{F}{q}$$

F is the force experienced by an object

q is the charge of an object

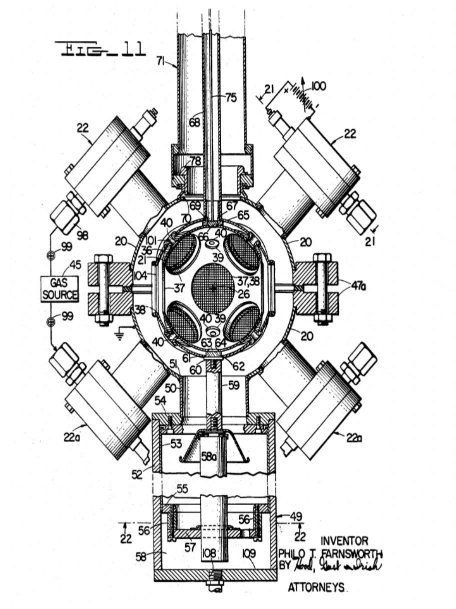
In the case of an IEC device, free electrons in the chamber will experience the electrical field, subsequently being acted upon by the force provided by the field. As stated by the British physicist Isaac Newton, force is proportional to acceleration. Therefore, as the electrons are being affected by the field, they are being accelerated. Furthermore, as these electrons are moving at high velocities, they will collide with molecules of the fuel gasses such as deuterium—a radioactive isotope of hydrogen. These high-energy collisions will knock electrons out of the gas molecule, resulting in ionization (Hawking).

These ionized deuterium molecules will also be accelerated, since they have a charge. This activates a chain reaction of ionization in the chamber—more and more molecules will be ionized through collisions. In the Farnsworth Hirsch Fusors, there is generally an inner grid that is positively charged. In reality, the positively charged cathode is negatively charged. The ionized gas molecules lack electrons, therefore are positively charged; they will be attracted to the negatively charged inner grid, otherwise the inner cathode (Britannica). In the presented fusion reactor, the design of the cathode makes the surface area small, reducing collisions with electrons. Moreover, since it is constructed with holes, ionized gas particles will travel through these holes, leaving through the other end of the cathode

With more gas molecules being ionized, more particles will also undergo the process of going through the cathode. The density of particles in the regions near the cathode will gradually increase, causing more collisions between ionized particles. Eventually, these ionized particles will fuse either through colliding with enough energy to overcome the coulomb barrier, or through quantum tunnelling.

Farnsworth Fusors- History of IEC Fusion:

The device—*Farnsworth Hirsch Fusor*—is a specific type of fusion reactor that is attributed to Philo T. Farnsworth, the inventor of the television. In the late 1950s to the early 1960s, Farnsworth developed this device as a fusion reactor, as they were a focus of international collaboration during that era. Despite Farnsworth being one of the critical people who contributed to the creation of such a reactor, he did not do so alone. Along with him, Dr. Robert Hirsch worked with Farnsworth's development team in the mid-1960s. Throughout his time on the team, Hirsch made numerous contributions and adjustments to the original design, which was later patented in 1968 as the *Farnsworth Hirsch Fusor*.



In the Farnsworth Hirsch Fusor, inner and outer grids are constructed from metal wires; the outer grid encompasses the inner grid. 4 devices on the peripherals of the chamber inject pressurized streams of deuterium, while excess gases are extricated using a strong vacuum (Farnsworth).

Fusion in the AECD:

In between two positively charged nuclei, there is an electrostatic repulsion that must be overcome to allow for the nuclei to fuse (Sinha et al). However, with significant amounts of energy, this barrier could be passed. The equation for calculating the amount of energy needed is:

$$U = \frac{1}{4\pi} \cdot \frac{N_1 N_2 e^2}{r}$$

U is the electrostatic potential energy of the Coulomb barrier

N_1, N_2 are respectively the atomic numbers of the nuclei

r is the distance between the centers of the nuclei

Using this equation to find the energy needed to bypass the coulomb barrier in deuterium-deuterium fusion gives a value of $600keV$. The kinetic energy gained by electrons after acceleration from the potential difference could be calculated using the equation:

$$E = qV$$

Since the particles undergoing acceleration are hydrogen ions, they have only one proton. Therefore, the charge will just be the elementary charge. It gives rise to the following equation:

$$E = eV$$

e is the elementary charge ($1.6 \cdot 10^{-19}C$)

The fusion reactor used in this experiment only has $15kV$ of direct current, thus the energy is only $15keV$.

Respectively, this is significantly less than the energy required to overcome the Coulomb barrier. As such, it is impossible to achieve fusion under conventional laws of physics. However, according to the French physicist de Broglie, particles will have wave-like properties if considered on the wave-like end of the Wave Particle Duality (Klute). Therefore, while travelling near another particle, the deuterium ions might appear in locations that cannot be reached by particles in the confines of classical physics; the deuterium nucleus might appear on the other side of the coulomb wall of the other deuterium nucleus, effectively causing fusion (Kumar).

Since in the design presented, the cathode is fraught with large gaps, ionized particles may pass through the cathode, and attempt to fuse once more. This increases the probability of fusion in the fusion reactor.

The probability of fusion in each interaction could be roughly estimated using the Gamow Factor, a method of calculation developed by the Russian-born physicist George Gamow (Gamow). For practical calculation, this factor could be simplified to:

$$P_{tunneling} \approx e^{\left(-\frac{2\pi N_1 N_2 e^2}{\hbar v}\sqrt{\frac{2m}{U_{barrier}}}\right)} \text{ (Yoon et al)}$$

N_1, N_2 are the atomic numbers of the fusion nuclei

$P_{tunneling}$ is the probability of fusion via quantum tunneling

$\hbar$ is the reduced Planck's constant

$$\hbar = \frac{h\ (Planck's\ constant)}{2\pi}$$

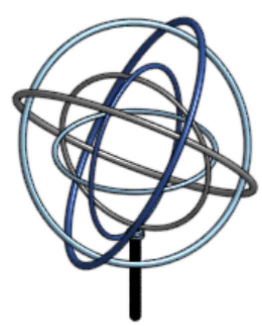
m is the mass of the deuterium nuclei (kg)

v is the velocity of the particles ($\frac{m}{s}$)

The $P_{tunneling}$ value is near 1, meaning that tunneling is probable in the fusion chamber.

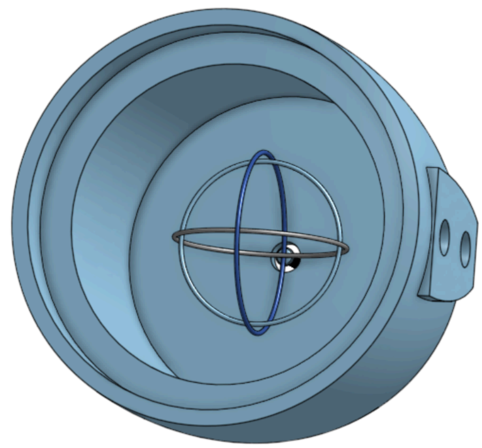
Integrated Outer Grid:

In the original designs of the Farnsworth Hirsch Fusor, there are two grids formed by soldered wire in the vacuum chamber: the inner grid and the outer grid. This method allows for an electric field to form between the cathode and anode. However, it is inherently complex since both grids in the chamber have to remain disconnected but at a uniform distance. First of all, uniform distance is very difficult to control and achieve. Moreover, this could be complicated to manufacture and is also more prone to degradation; the outer grid is constructed with soldered wire and will erode due to high-energy ion bombardment while the device is operating (Moore). It is apparent that both grids will be prone to erosion from ion bombardment, but repairing the grids when they are encompassed in one another is



more complex than simply repairing one grid. Considering that there is electricity in the wires, there will be Ohmic heating from the current (Von Meier). In the original designs of the Farnsworth Hirsch Fusor, the outer grid is constructed from wire and has an overall lower volume. Thus, this will create a high current density, which will exacerbate local heating. Local heating is detrimental to the functionality of the fusor because it will expedite grid erosion.

Conversely, in the design of the AECD, the outer grid is integrated into the vacuum chamber walls. This means that the outer grid has a greater volume. As a result, a lower current density will occur. Since the walls of the AECD chamber have a large surface area, they can dissipate heat from Ohmic heating into the environment better. This prevents grid erosion from localized heating. The larger surface area not only decreases the effects of localized heating, but it also enhances the ion bombardment problem. This issue itself reduces the efficiency of the reactor since the ions being bombarded onto the grid are the same hydrogen ions that should be used for fusion. However, it is often inevitable in an inertial electrostatic confinement device, because when ionized molecules have significant amounts of kinetic energy, the work done by the electric field is not enough to decelerate the molecule in the opposite direction of its motion. In the Farnsworth Hirsch Fusor, the outer grid has a smaller surface area and is closer to the inner grid. This will result in more ions being bombarded on the limited surface area, subsequently accelerating the degradation of the grid. However, with more surface area, the ion bombardment is more dispersed, subsequently resulting in less concentrated grid erosion.



IEC and MEC:

In fusion reactors, there are two main approaches to electrostatic confinement: inertial electrostatic confinement (IEC) and magnetic electrostatic confinement (MEC). In IEC, the strong electric field will ionize and accelerate deuterium ions. On the other hand, MEC devices implement magnetic fields to confine ionized molecules. MEC is a more widely adopted approach, yet both of these solutions have benefits and drawbacks.

Magnetic fields prevent ions from colliding with grids, subsequently preventing problems relating to ion bombardment (Jones). This subsequently allows for higher efficiency because molecules capable of fusion are less likely to lose energy by colliding with grids. Instead, they will be accelerated by the strong magnetic field, and will be recirculated into the locations densely packed with deuterium ions (Furth). As molecules recirculate and accelerate, they will gain velocity and kinetic energy. Eventually, the kinetic energy is enough to overcome the coulomb barrier, meaning that the ions will directly fuse when in contact with each other. In IEC devices, most molecules will not gain enough energy to break the coulomb barrier. For this reason, fusion using IEC mainly resorts to the quantum tunnelling of ions (Meulenberg). Because the probability of fusion via quantum tunnelling is significantly lower than the probability of fusion when the ions have enough kinetic energy to bypass the coulomb barrier, MECs are more efficient with each fusible molecule.

The fusion efficiency of magnetic electrostatic confinement is an apparent benefit, yet there are major limitations to this approach as well. Magnetic confinement requires complex magnetic fields to be implemented. These systems are more complex than accelerating molecules using electric fields, therefore, they are less suitable for small modular reactors (SMR). This is exemplified by a common MEC design, the Tokamak. The Tokamak is a ring that utilizes strong magnetic fields to confine and accelerate deuterium ions (Clery). Out of all the fusion reactor designs, it is one of the closest to achieving sustained net positive power output. However, for application in small communities, modular fusion reactors do not require sustained power output. The immense costs outweigh the benefits brought forth.

The principal benefit of inertial electron confinement is its simplicity. Since only two grids with high potential difference are needed for accelerating electrons, fewer costs and maintenance will be required. The simplicity of IEC is apparent not only because of the simple grid acceleration setup but also because it is capable of preventing more hidden costs. MEC designs implement electric fields in conjunction with magnetic fields, with the purpose of magnetic fields being to restrict the movement of ions. In these reactors, the primary role of accelerating ions still belongs to electric fields. Therefore, if the fields are misaligned, the ions may leave the ideal path, and hit grids or walls. Tuning the magnetic field in MEC reactors exceeds the capabilities of people in remote communities. As a result, it is unrealistic to implement. On the other hand, IEC fusors simply consist of a cathode and an anode. It is significantly easier to maintain, making it more suitable for small communities.

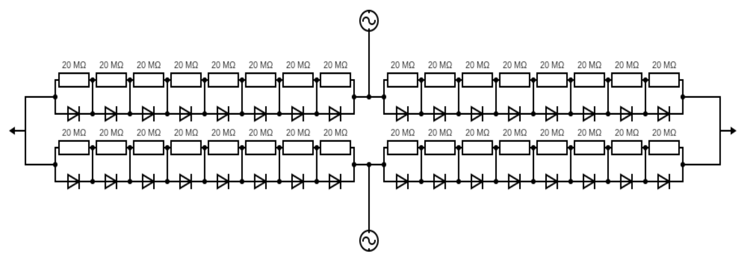
Success Criteria:

	Specification	Significance	Assessment	Data collection type	
				Objective	Subjective
Cost	The ACED must be built with a total cost of less than 1000 dollars (CAD).	This rule is present, because the main purpose of the ACED is to demonstrate the potentials of a low-cost inertial electrostatic confinement device. By establishing this specification, the production of the experimental model will likely have a lower cost. Furthermore, the value of 1000 is set because the components that are needed to realize an IEC setup are simple; aluminum and stainless steel grids, a vacuum pump, and a transformer.	This criteria could be assessed by verifying the costs via receipts. If the sum of the costs is less than 1000 dollars, then this specification is met.	Yes	No
Grid Isolation	The inner and outer grids must not be in contact with each other.	This design specification is set, because for electric fields to appear, the two grids have to be separated. If it is not, then the current will just travel from the inner grid to the outer grid (conventional current).	There are two methods to verify this. The first method of verifying the grid isolation properties is by visually observing the components. If it is observed that there are any points of contact between the two parts, then this specification is not met. On the other hand, low voltage electricity could be applied to the inner or outer grid. If there is no current measured in the alternate grid, then this is successful.	Yes	No
Pressure	The pressure in the vacuum chamber should reach 1.3 pascals.	A low pressure is necessary for successful fusion regardless of electrostatic confinement method. This is because in the presence of unwanted gas molecules, ionized deuterium will collide with unwanted gasses, dissipating the kinetic energy that it gained through electric field acceleration. According to reports from institutions that conducted relevant research, a pressure of 1.3 pascals can allow for fusion to happen.	This specification could be assessed by connecting the vacuum pump to the chamber, and by letting the pump function for approximately 10 minutes. If the pressure shown on the vacuum gauge is 1.3 pascal or an equivalent, then this specification is met.	Yes	No
Plasma generation	Plasma should appear inside the inner grid of this IEC device.	Plasma is composed of ionized gasses and free moving electrons. These particles are necessary in D-D fusion, and in the case of IEC D-D fusion, the plasma will be composed of accelerated deuterium ions and electrons. If there is a plasma, then that means the electrical field functions properly, and is capable of accelerating ions and electrons.	Plasma could be observed, and this specification could be verified by recording observations. If the AECD is emitting light from the inner grid in the form of a clustered ball, then it is considered capable of generating plasma.	Yes	No

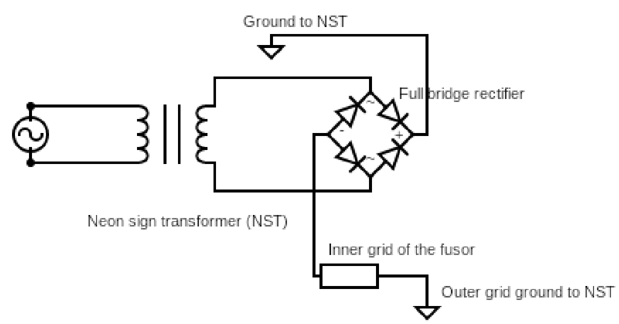
Methodology - High Voltage Rectification:

For a constant stream of charge, direct current must be used instead of alternating current. This results in the fusion reactor not being able to use current directly from the wall. Moreover, the voltage supplied in sockets is about $110\ V$, whereas fusion requires at least more than $5\ kV$ of potential difference between the inner and outer grids. Conventional transformers are not capable of amplifying voltage to the kilovolt range. Thus, neon sign transformers (NST)—a type of obsolete transformer, capable of providing high voltage for neon signs have to be used.

Neon sign transformers transform low-voltage AC to high-voltage AC; this still does not provide DC current. To transform the electricity from AC to DC, full bridge rectifiers have to be used. This is because the simpler counterparts, half-wave rectifiers, only transform parts of the sinusoidal alternating current to direct current.



To construct a full-wave rectifier, diodes(GP02-40-E3/73) and resistors(VR68000002005JAC00) have to be placed in parallel. For this experiment, $20M\Omega$ resistors are being used. They should be placed with resistors in the configuration below.



The above diagram features a full wave rectifier. It will be connected to the transformer, and to the fusion chamber.

Methodology - Chamber Design & Manufacturing:

In this reactor design, the outer grid is the chamber. This design is implemented to lower the costs of manufacturing. As a prototype, this low-cost fusion reactor uses CNC machining to produce the chamber.

When designing the chamber, it is imperative to consider the distance between the outer and inner grids. This is critical because the distance between the grids directly affects the electric field strength of the chamber. It is best to have the two grids maintain a uniform distance so that particles are not erratically accelerated. This will be done through OnShape, a CAD software.

After the chamber has been successfully CNC machined, it is necessary to drill and tap holes. By doing so, the chamber could be connected to the vacuum and vacuum gauge. After tapping these holes, male plugs with corresponding threads could be inserted. However, it is necessary to apply Teflon tape onto the plugs, just to ensure that gasses won't enter the chamber through gaps.

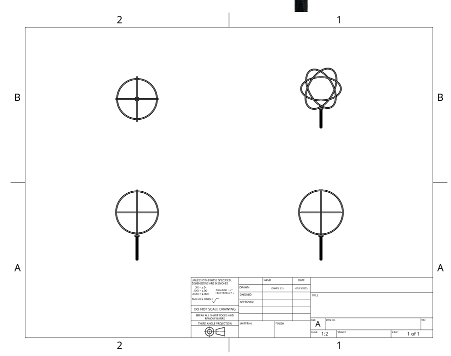
Methodology - Vacuum:

A double-stage vacuum pump will be used to lower the number of unwanted molecules in the reaction chamber. The goal is to achieve pressure levels of several microns.

The vacuum pump will be external to the chamber and will be connected via vacuum tubing. To ensure that leaking occurs minimally, Teflon tubing should be attached to any plugs.

Methodology - Inner Grid Manufacturing:

12-gauge stainless steel wire will be twisted around 1-inch diameter tubing. The tubing with the wire will be cut vertically, creating stainless steel rings. These rings will be soldered together, all connected to an M3 screw.



Stainless steel features different metals bonded together via metallic bonding. The resultant alloy is not prone to reaction, making it harder to solder. Therefore, specialized flux is needed to craft the inner grid.

Methodology - Assembly:

The inner grid will get inserted into the chamber, with the other end of the screw being exposed. A ceramic tubing will insulate the screw and the outer grid. This way, current could be provided to the inner grid. After this process, the chamber will be sealed. Other than the male plugs that enable connection with the vacuum pump, every other potential leakage will be sealed with permanent glue.

A cable with the live, ground, and neutral wires will be connected to the corresponding plugs on the NST. The two screw terminals on the secondary side of the transformer should be connected to the AC input of the full wave rectifier. With the NST connected to the full wave rectifier, the negative terminal of the rectifier should be connected to the inner grid. The positive terminal should be wired to ground. Furthermore, the outer grid should also be connected to ground. By completing this installation, the potential difference between the outer grid and the inner grid should be equal to $15kV$.

After completing the electrical part of this build, the vacuum chamber should be the main focus. To start the pump, mechanical oil should be put into the vacuum pump. This serves as a coolant. Furthermore, vacuum tubing should be used to connect the pump to the chamber. The vacuum properties could be enhanced by applying Teflon tape on plugs, as well as having restricting rings on the tubes. The vacuum should be turned on until the pressure in the chamber is ideal.

Once the above processes are complete, plug the NST into a wall socket. If everything is functional, then a ball of plasma should appear inside the inner grid. To conduct fusion, deuterium has to be injected into the chamber prior to the operation of the device.

Success Criteria Evaluation:

<table>
<tr><th rowspan="2"></th><th rowspan="2">Specification</th><th rowspan="2">Evidence</th><th rowspan="2">Explanation</th><th colspan="2">Completion</th></tr>
<tr><th>Y/N</th><th>Degree of completion</th></tr>
<tr><td>Cost</td><td>The ACED must be built with a total cost of less than 1000 dollars (CAD).</td><td><table><tr><th>Item</th><th>Price</th><th>Sum</th></tr><tr><td>Chamber</td><td>293.85</td><td></td></tr><tr><td>Stainless steel wire</td><td>14.99</td><td></td></tr><tr><td>M3 screw set</td><td>23.99</td><td></td></tr><tr><td>NST</td><td>256.99</td><td>694.44</td></tr><tr><td>Diodes</td><td>12</td><td></td></tr><tr><td>Resistors</td><td>18.42</td><td></td></tr><tr><td>Wire</td><td>74.2</td><td></td></tr></table></td><td>By reviewing documents such as receipts and invoices, the prices of different items were found. The sum of the costs amounts to 694 (CAD), which is less than the limit of 1000.</td><td>Y</td><td>Completed to the greatest extent</td></tr>
<tr><td>Grid Isolation</td><td>The inner and outer grids must not be in contact with each other.</td><td>1. By visual observation, the inner and outer grids are completely disconnected.
2.<table><tr><th>Trail</th><th>Result</th></tr><tr><td>#1</td><td>No reading</td></tr><tr><td>#2</td><td>No reading</td></tr><tr><td>#3</td><td>No reading</td></tr></table></td><td>According to the first piece of visual observation, there are no places where the inner and outer grids are connected. This means that it is likely that there are any electrical connections. This is furthermore verified with a test composed of three trials. In this test, voltage is applied to the inner grid, and voltage readings will be made at the outer grid. In all three trails, there are no readings, meaning that there are no electrical connections between the inner and outer grids.</td><td>Y</td><td>Completed to the greatest extent</td></tr>
<tr><td>Pressure</td><td>The pressure in the vacuum chamber should reach 1.3 pascals.</td><td><table><tr><th>Trial</th><th>Pressure (kPa relative to atmosphere)</th></tr><tr><td>#1</td><td>-99</td></tr><tr><td>#2</td><td>-100</td></tr><tr><td>#3</td><td>-98</td></tr></table></td><td>After conducting three trials, it is observed that the chamber can reach a pressure of up to $-100\ kPa$. This is approximately $1325\ Pa$. Although this is considered a very low pressure, it does not reach the threshold needed for fusion.</td><td>N</td><td>Not yet completed, could be reached with more refinement.</td></tr>
<tr><td>Plasma generation</td><td>Plasma should appear inside the inner grid of this IEC device.</td><td>N/A</td><td>The high voltage component was not tested due to safety considerations.</td><td>N</td><td>Unknown, could only be assessed after testing in a safe environment.</td></tr>
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Project Evaluation:

One of the most important components of this project is to provide an open-source, affordable device capable of generating plasma and possibly conducting fusion. The relevant information and files are all open-sourced; therefore, the project was successful in this regard. Furthermore, with intentional design decisions that lower the costs of manufacturing, the AECD could be produced with less than $1000 CAD. The AECD prototype is capable of reaching vacuum levels near that of the expected $-\ 103\ kPa$ (reached $-\ 100\ kPa$). These factors indicate that the AECD prototype is likely able to generate plasma and facilitate fusion with D-D fuel.

There are forums dedicated to the manufacturing of Farnsworth-Hirsch Fusors and similar devices. However, there is little information available that is synthesized and documents the specifics of manufacturing these reactors. Through the process of researching and synthesizing information, relevant knowledge regarding fusion is obtained. With this information, researchers in the future could potentially develop devices that are idiosyncratic to their needs.

Despite being able to meet most of the criteria, the high voltage component of the prototype AECD is not assessed. This is because no facilities capable of providing safe testing were available. This subsequently results in the plasma generation and fusion capabilities of the AECD being tested with experimental data.

Ultimately, the design of the AECD is focused on lowering the costs of production. This directly hinders the capabilities of the products. This is exemplified by the adoption of an NST for the high voltage module. NSTs can only provide voltage levels of $15kV$. Potential differences of this magnitude are not enough to accelerate particles to energy levels required for fusion, directly inhibiting fusion via overcoming the Coulomb Barrier.

Next Steps:

With assistance from researchers and local institutions, the high voltage component of the AECD could be tested safely. By doing so, experimental data regarding fusion could be obtained. After the high voltage components are tested, a research/investigation could be conducted regarding the effectiveness of fusion at different voltages, or with different fuels. These extensions will make the AECD closer to being able to provide economical fusion energy, as amendments could be made to optimize fusion rates.

Despite being close to the ideal atmosphere level for fusion, the chamber is still excessively filled with unwanted gas molecules. With assistance from professionals, the vacuum system could be altered to meet the atmospheric conditions for nuclei to fuse.

The current AECD does not feature a gas injection system. Such systems are important to practical fusion, because they allow for deuterium gas to be effectively supplied. Without a proper injection apparatus, D-D fuel will likely be dissipated by the vacuum pumps. An injection system could be integrated into the AECD, allowing for fusion rates to increase

References

Bais, Sander. "The Splendid Diversity of Condensed Matter." *Power of the Invisible: The Quantessence of Reality*, Amsterdam University Press, 2024, pp. 487–522. *JSTOR*, http://www.jstor.org/stable/jj.12124946.20. Accessed 23 Feb. 2025.

Bhatt, Kapil, et al. "Comparative Study of the Models Used for Calculation of Transport Characteristics in Metal-Insulator-Metal/Miim Diodes." *Advanced Science Letters*, vol. 21, Aug. 2015, pp. 2570–73, https://doi.org/10.1166/asl.2015.6426. Accessed 21 Feb. 2025.

Britannica. "Electric Current | Formula & Definition." *Encyclopædia Britannica*, 17 Aug. 2018, www.britannica.com/science/electric-current. Accessed 12 Feb. 2025.

Clery, Daniel. "ITER's $12 Billion Gamble." *Science*, vol. 314, no. 5797, 2006, pp. 238–42. *JSTOR*, http://www.jstor.org/stable/20031504. Accessed 14 Feb. 2025.

Culham centre for fusion energy. *Culham Centre for Fusion Energy (CCFE)*. 2025, ccfe.ukaea.uk. Accessed 29 Mar. 2025.

European Synchrotron Radiation Facility. *European Synchrotron Radiation Facility (ESRF)*. 2025, www.esrf.fr/home.html.

Farnsworth, Philo T. *Electrical Discharge Device for Producing Interactions Between Nuclei*. US Patent 3,386,883, issued 4 June 1968. *Google Patents*, https://patents.google.com/patent/US3386883A/en. Accessed 18 Mar. 2025.

Furth, H. P. "Magnetic Confinement Fusion." *Science*, vol. 249, no. 4976, 1990, pp. 1522–27. *JSTOR*, http://www.jstor.org/stable/2877808. Accessed 14 Feb. 2025.

Gamow, George. "The Principle of Uncertainty." *Scientific American*, vol. 198, no. 1, 1958, pp. 51–59. *JSTOR*, http://www.jstor.org/stable/24942034. Accessed 12 Feb. 2025.

General Atomics. "DIII-D National Fusion Facility." *General Atomics*, 2025, www.ga.com/magnetic-fusion/diii-d. Accessed 29 Mar. 2025.

Hawking, Tom. "WISHING ON A BOTTLED STAR." *ReNew: Technology for a Sustainable Future*, no. 160, 2022, pp. 49–55. *JSTOR*, https://www.jstor.org/stable/48747010. Accessed 12 Feb. 2025.

Hazeltine, Richard D., et al. “The Advanced Tokamak.” *Science*, vol. 281, no. 5378, 1998, pp. 784–784. *JSTOR*, http://www.jstor.org/stable/2896202. Accessed 14 Feb. 2025.

Hull, Richard. “The Farnsworth/Hirsch Fusor.” *Belljar*, Belljar, 29 Mar. 1997, www.belljar.net/634fusor.pdf. Accessed 10 Feb. 2025.

Institute of Plasma Physics, Chinese Academy of Sciences. “Institute of Plasma Physics.” *Chinese Institute of Sciences*, 2025, english.ipp.cas.cn. Accessed 29 Mar. 2025.

J.M.K.C. Donev et al. “Access to Electricity.” *Energy Education*, Energy Education, 24 Apr. 2016, energyeducation.ca/encyclopedia/Access_to_electricity#:~:text=As%20well%2C%20most%20of%20the,electricity%20living%20in%20rural%20areas. Accessed 16 Feb. 2025.

Jones, R. “Plasma Confinement with Electrical and Magnetic Fields.” *Transactions of the Kansas Academy of Science (1903-)*, vol. 95, no. 1/2, 1992, pp. 122–27. *JSTOR*, https://doi.org/10.2307/3628027. Accessed 14 Feb. 2025.

Klute, Markus. *Introduction to Nuclear and Particle Physics*. Sept. 2020, ocw.mit.edu/courses/8-701-introduction-to-nuclear-and-particle-physics-fall-2020/64c30ac67eed358ce881c26506539bdd_MIT8_701f20_lec9.8.pdf. Accessed 12 Feb. 2025.

Korea Institute of Fusion Energy. “Korea Superconducting Tokamak Advanced Research (KSTAR).” *Korean Institute of Fusion Energy*, 2025, www.kfe.re.kr/menu.es?mid=a20202030100. Accessed 29 Mar. 2025.

Kulcinski, Gerald L., and John F. Santarius. “Non-Electric Applications of the Inertial Electrostatic Confinement Fusion Concept.” *Fusion Science and Technology*, vol. 64, no. 2, Aug. 2013, pp. 365–72, https://doi.org/10.13182/fst13-a18104. Accessed 23 Feb. 2025.

Kumar, N. “COLD FUSION: IS THERE A SOLID STATE EFFECT?” *Current Science*, vol. 58, no. 15, 1989, pp. 833–35. *JSTOR*, http://www.jstor.org/stable/24094728. Accessed 12 Feb. 2025.

Liou, Joanne. “What Are Small Modular Reactors (SMRs)?” *IAEA*, IAEA, 14 Sept. 2023, www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs#:~:text=Language-,Nuclear%20Explained,Vargas/IAEA). Accessed 19 Feb. 2025.

Massachusetts Institute of Technology. “Plasma Science and Fusion Center (PSFC).” *Massachusetts Institute of Technology*, 2025, www.psfc.mit.edu. Accessed 29 Mar. 2025.

Meulenberg, A. “Extensions to Physics: What Cold Fusion Teaches.” *Current Science*, vol. 108, no. 4, 2015, pp. 499–506. *JSTOR*, http://www.jstor.org/stable/24216594. Accessed 14 Feb. 2025.

MOORE, WALTER J. “THE IONIC BOMBARDMENT OF SOLID SURFACES.” *American Scientist*, vol. 48, no. 2, 1960, pp. 158A – 133. *JSTOR*, http://www.jstor.org/stable/27827533. Accessed 23 Mar. 2025.

National Institutes for Quantum Science and Technology. *JT-60SA Fusion Research*. 2025, www.qst.go.jp/site/qst-english.

NIST. *EEEL Safety Rules for Moder Ate and High Voltages*. 2008, www.nist.gov/system/files/documents/el/isd/mmc/high_voltage_rules_revised.pdf. Accessed 23 Mar. 2025.

Rafelski, Johann, and Steven E. Jones. “Cold Nuclear Fusion.” *Scientific American*, vol. 257, no. 1, 1987, pp. 84–89. *JSTOR*, http://www.jstor.org/stable/24979424. Accessed 23 Feb. 2025.

Sinha, K. P., and A. Meulenberg. “Laser Stimulation of Low-Energy Nuclear Reactions in Deuterated Palladium.” *Current Science*, vol. 91, no. 7, 2006, pp. 907–12. *JSTOR*, http://www.jstor.org/stable/24094288. Accessed 12 Feb. 2025.

“Small Modular Reactors.” *Ontario*, Ontario, 21 Apr. 2021, www.ontario.ca/page/small-modular-reactors#:~:text=A%20typical%20SMR%20would%20generate%20between%202,power%20for%20a%20village%20or%20small%20city.&text=SMR%20technology%20has%20the%20potential%20to%20bring,may%20currently%20rely%20on%20expensive%20diesel%20power. Accessed 20 Feb. 2025.

Von Meier, Alexandra. *Electric Power Systems: A Conceptual Introduction*. Wiley-IEEE Press, 2006. *Google Books*, books.google.com/books/about/Electric_Power_Systems.html?id=bWAi22IB3lkC. Accessed 22 Mar. 2025.

Yoon, Jin-Hee, and Cheuk-Yin Wong. "Relativistic Modification of the Gamow Factor." *Phys. Rev. C*, vol. 61, no. 4, American Physical Society, 2000, p. 044905, https://doi.org/10.1103/PhysRevC.61.044905. Accessed 15 Feb. 2025.