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THE FUTURE OF NUCLEAR ENGINEERING

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1.1 ABSTRACT

Today, nuclear power refers to the splitting of large uranium atoms into smaller atoms with a net release of energy. Tomorrow, nuclear power will refer to the combining of hydrogen into larger atoms with a net release of energy. Nuclear power's future is fusion. The Mechanical Engineers of tomorrow will need to be familiar with the process of creating and harnessing the energy from a fusion reaction.

During the oil shortage in the 1970's, America scrambled to initiate alternative methods of producing power. Nuclear fusion was one of them. As time passes, the solution to the world's energy crisis presses the countries of the world to find alternative forms of energy; nuclear fusion may contain the answer.

In the near future, the field of fusion will open up and a new wave of engineers will flood into this field. Mechanical engineers will lead the way with advances in materials, computational fluid dynamics, finite element analysis for thermal and structural systems, and heat transfer designs to optimize nuclear fusion reactors and power plants.

All this effort is in anticipation of creating a sustained fusion reaction that can generate enough heat to transfer to steam in order to generate electric power to sustain the fusion reaction and introduce power to the grid.

2.1 OVERVIEW OF NUCLEAR FUSION

The sun is our inspiration for nuclear fusion[1]. The sun fuses small ions of hydrogen into larger ions of helium. The combination of the smaller atoms release large amounts of electromagnetic energy in all spectrums. In order to create fusion in labs or in a commercial reactor we attempt to mimic the conditions on the sun.

The large amounts of energy that is released during a nuclear reaction stems from the binding energy in atoms. When protons and neutrons come together to form a nucleus of an atom there is a certain atomic weight associated with the nucleus. This atomic weight is less than the combined weight of the protons and neutrons. The difference in mass becomes energy. The fusion of two atoms yields a net release of energy, hence the ability to harness fusion power.

Different ions undergoing a fusion reaction release different amounts of energy. Today the fuel used for the fusion reaction is a deuterium/tritium combination. Both deuterium and tritium are isotopes of hydrogen. An isotope of an element has the same number of protons, but a different number of neutrons. Deuterium can be found in everyday seawater, for more information see **Section 2.**2. Tritium is produced by bombarding lithium with high-energy neutrons, for more information see **Section 3.**1.

Princeton Plasma Physics Laboratory (PPPL) has claimed that by using deuterium and tritium as fuel, they have produced fusion reactions that have released over 10 Mega-Watts (MW) of power[2]. This amount of power released was not sustained for more than one second[3]. To generate heat for a power plant, a sustained fusion reaction is necessary.

By-products of a fusion reaction are highly energized neutrons and helium atoms, as seen in *Figure 1*. Approximately one-fifth of the energy is kinetic energy of the helium ion and four-fifths is the kinetic energy of the neutron[2].

The nuclei of the atoms must come into close proximity with one another and have enough excess energy to produce fusion. All nuclei are positively charged. By overcoming the electrostatic forces of repulsion, the ions are able to get into close enough proximity needed for fusion to occur. To facilitate this, the hydrogen gas is heated to the point where the kinetic energy of the particles is greater than the force of electrostatic repulsion[4]. In order for this to be accomplished the super-heated gas must be brought to temperatures over 100 million degrees centigrade (ºC), the ignition temperature[5]. As the temperature is increased, the probability of a fusion reaction is increased. To date the highest plasma temperature attained is 510 million ºC at PPPL[6].

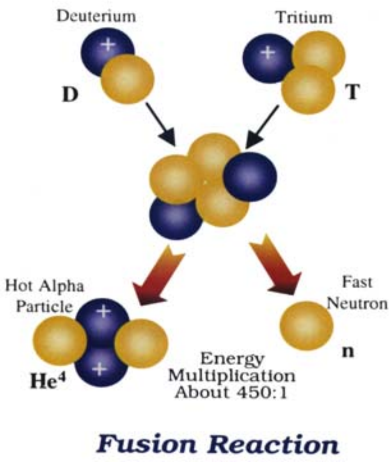

Figure 1: Deuterium-Tritium Fusion Reaction (Courtesy of PPPL)

A Tokamak (see *Figure 2*) is a doughnut shaped device in which the fusion reaction takes place. The Tokamak has wires that generate a magnetic field inside of it. This magnetic field contains the super-heated plasma. The gas mixture is super-heated, ripping the electrons from the atoms, ionizing the gas, thus making it into plasma. This positively charged plasma can be magnetically confined allowing the high temperatures necessary for nuclear fusion to occur[7].

Figure 2: Magnetic Confinement Device Model, a Tokamak (Courtesy of PPPL)

In summary, a deuterium and tritium mixture is injected into the Tokamak. The mixture is heated until it ionizes creating the plasma. The plasma current is confined by magnetic fields and is continually heated. The plasma is heated until it reaches the temperature needed for fusion to occur. Deuterium and tritium ions come together to form a helium ion, a neutron, and a net release of energy. The helium ion continues through the plasma heating it further. The continual addition of heat should be enough to sustain the fusion reaction. The neutron, because of its lack of charge, leaves the magnetic confinement and releases its heat in a neutron absorbing material. A series of heat exchangers extracts this heat from the neutron-absorbing material, producing steam. The steam drives a turbine with electric power output. Some of the electric power goes back to sustaining the magnetic field while most is introduced to the power grid[8].

2.2 NUCLEAR FUSION AND FISSION

Nuclear Fusion poses many advantages over nuclear fission. Fusion produces less radioactive byproducts. Fusion has the capability of producing larger quantities of power[6]. The main fuel for the fusion reaction is from heavy water. Heavy water contains deuterium in lieu of hydrogen atoms. Heavy water, which is present in approximately 1% of seawater, is abundant[5]. Extraction of the deuterium is possible anywhere in the world that has access to seawater. In addition, tritium could possibly be extracted as a by-product of the fusion reaction, see **Section 3.1**.

3.1 CREATING THE REACTION

The fusion reaction occurs within the plasma contained by the Tokamak. The probability that a fusion reaction will occur is proportional to the temperature of the plasma. In addition, there are ways of manipulating the plasma within the Tokamak to induce a reaction.

Mechanical Engineers will play a pivotal role in designing Tokamaks that can contain extreme temperatures (see *Figure 3*). Even though the plasma is contained inside a magnetic bottle, to generate steam extraction of the heat from inside of the Tokamak is necessary.

The fusion reaction between deuterium and tritium produces an extra neutron that will exit the magnetic field. A medium that will absorb the stray neutron converting the kinetic energy into heat energy, and as scientists plan, produce more fuel for the reaction.

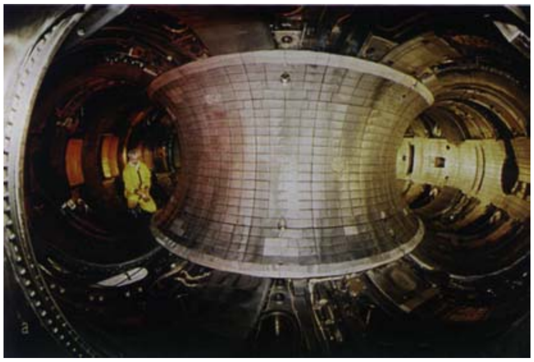

Figure 3: Interior of the Tokamak Test Fusion Reactor (TFTR) (Courtesy of PPPL)

Bombarding lithium with high-energy neutrons forms tritium. This is also, where radioactivity becomes a concern. If the lithium does not absorb the neutron and the neutron then passes to the Tokamak, then over time the Tokamak can become radioactive.

The surface surrounding the plasma will be subjected to an estimated 25 million watts per square meter of heat flux. There are two typical approaches to containing the reaction. One approach utilizes a "first wall" that will have a layer of lithium behind another material, the first wall. The other could possibly have a layer of liquid lithium directly surrounding the reaction[9].

The approach that uses a "first wall" prior to the blanket of lithium has some drawbacks. The wall will have to be a material that can withstand high temperatures, and successive bombardments with high-energy particles. In addition, as the neutron travels through the material the wall itself could become radioactive leading to structural weaknesses. As demonstrated in fission reactors materials exposed to high-energy neutrons, become brittle after prolonged exposure.

The other approach being researched by PPPL, University of California – San Diego, Oak Ridge National Laboratory, Sandia National Laboratory, and others deals with surrounding the fusion reaction magnetic bottle with a liquid layer of lithium[9]. According to their research, the liquid layer of lithium will have many benefits to the production of fusion power. These benefits include the extraction of the neutron and formation of tritium, the possible absorption of the helium ion produced during the deuterium-tritium reaction, elevated plasma temperatures, and increased plasma confinement.

None of these benefits will do any good unless extraction of the tritium from the liquid lithium becomes a reality. In addition, the heat gained by the lithium can be exchanged to another medium to facilitate steam generation[6].

Mechanical Engineers will be called upon to design heat exchangers for the liquid lithium. In turn, Mechanical Engineers will help in the design of the tritium extraction process from the lithium.

Lithium, being a highly reactive liquid metal, such as sodium, reacts violently with water. Therefore, well-designed heat exchangers are necessary, to insure that no contact between air and water occurs with the lithium. The other aspect of the design is that the heat exchanger will have to be as efficient as possible without impeding on the safety issue. The more efficient the heat exchanger system outside the fusion reactor, the earlier nuclear fusion will become a commercial reality. Mechanical Engineers will design the heat exchangers, similar to how the heat exchangers are designed for today's nuclear fission plants.

There are designs in existence today for liquid sodium heat exchangers that operate with nuclear fission power plants. Modification of these designs could be possible to use liquid lithium as a working fluid. The temperature of liquid sodium in a fission reactor heat exchanger is typically around 650ºC. The heat flux bombarding the lithium could produce temperatures exceeding this and the melting point of Lithium, which is 1342ºC, producing lithium in the vapor state. A different method utilizing radiation cooling could possibly be used at these extreme temperatures[10].

4.1 FINITE ELEMENT ANALYSIS

Mechanical Engineers are generally one of the few groups of students trained in using different Finite Element Analysis (FEM) software packages. In school, structural, thermal, electro-magnetic, and fluid analyses are included in every Mechanical Engineering student's curriculum. Each one of these has their own impact on fusion design[11].

Evaluation of the fusion reaction chamber will need to be performed, see *Figure 4*. Creating a vacuum within the reaction chamber is the only way to have pure plasma within the chamber. This in turn puts much stress on the reaction chamber structure. The more efficient the construction the sooner nuclear fusion will become a reality. Continuing to perform structural analysis on the reaction chambers with increasing computer power will ensure the materials are used in an optimized manner[11].

The reaction chamber as well as the liquid lithium layer will be exposed to extreme amounts of thermal gradients. By using FEM to model and simulate the system, various designs can be evaluated without having to invest much capital. This thermal analysis will enable efficient design[12].

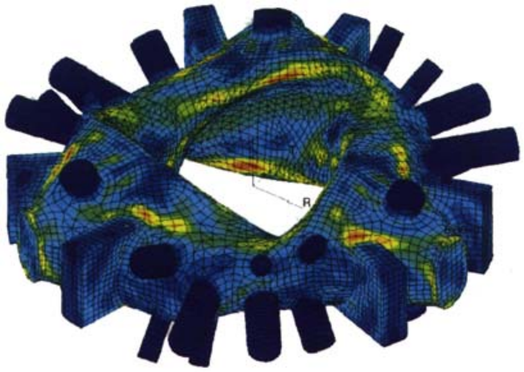

Figure 4: Finite Element Analysis of Vacuum Vessel Stress (Courtesy of Princeton Plasma Physics Laboratory)

Complex fluid analysis will also be needed to model the flow of plasma through the magnetic confinement, see *Figure 5*. The plasma shape is a very important aspect of the probability that fusion reactions will occur[13]. The charged nature of plasma will lead to complex analyses. In addition, one of the major drawbacks to magnetically confined fusion experiments today is the escaping of some plasma through the magnetic field; this is referred to as confinement quality[9]. Since the 1970s, the confinement quality has been increasing and is projected to reach practical ranges in the near future. By continuing to use Computational Fluid Dynamics (CFD), confinement quality can continue to increase rapidly[14].

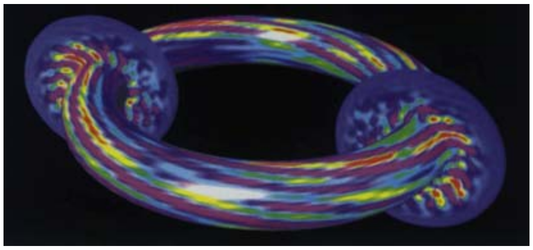

Figure 5: Modeled Plasma Flow and Temperature Gradients (Courtesy of Princeton Plasma Physics Laboratory)

5.1 POWER SYSTEM CONSIDERATIONS

As in nuclear fission, mechanical engineers will have to design the heat exchangers associated with generating steam and ultimately the entire power generating cycle.

In order to make nuclear fusion power more promising for the near future, maximization of the efficiency of the electric power generating process will have to take place. The concept of magnetic confinement nuclear fusion consumes large amounts of power from the start. There is electric power needed to produce and sustain the magnetic field. In addition, electric current runs through the plasma facilitating Ohmic heating to a certain extent. The intent is to have the reaction self-sustaining, meaning that the kinetic energy from the released helium ion converts into enough heat energy to keep the plasma above the ignition temperature.

By increasing the efficiency that heat exchangers and turbines operate at, as mechanical engineers have been doing for years, the amount of electrical power output can be optimized. This in turn yields more power available for distribution and makes nuclear fusion commercially viable.

6.1 BEYOND THE TOKAMAK

Tokamaks are just the beginning when it comes to magnetic confinement fusion reactions. Throughout the world, different variations on the magnetic chamber are being built and explored[5].

At PPPL, the National Spherical Torus Experiment began operation in 1999. This device is shaped like a large sphere with a hole through the middle, similar to a cored apple. This variant shape allows plasmas to behave differently then they would within a Tokamak[15].

In addition, the National Compact Stellarator Experiment (NCSX) at PPPL is examining different plasma flows. The NCSX will produce a helical plasma flow around the doughnut-shaped flow. The helical-field is produced through various modular coils that maintain the magnetic field[16].

Many other design concepts for new plasma flows as well as variations on structures are in the making around the globe. The Tokamak is an excellent device to study plasma physics and explore the possibility of fusion power in the future[17].

7.1 INERTIAL CONFINEMENT FUSION

Another concept for fusion production does not deal with magnetic fields; instead, it is confined inertially. The sun and other stars create a fusion reaction through gravitational confinement, a Tokamak through magnetic confinement, and this concept through inertial confinement. There are four stages in the production of a fusion reaction through inertial confinement[13].

Stage one: A fuel pellet is bombarded with lasers or an ion beam uniformly from all directions simultaneously. This fuel pellet could be a metallic substance such as palladium that is enriched with deuterium. At standard temperature and pressure, palladium can absorb up to 900 times its own volume in hydrogen[18]. The surface of the fuel pellet will be super-heated and the rapid vaporization of the surface will force inward on the fuel pellet (see *Figure 6*).

Stage two: the vaporizing force compresses the fuel pellet further.

Stage three: The implosion continues to the core where the density is increased and the temperature reaches over 100 million °C. The large amounts of hydrogen are compressed into a very small volume and begin to fuse.

Stage four: The fuel reaches the ignition temperature and nuclear fusion is reached. A large outburst of energy is then absorbed to generate heat.

This potential form of fusion has much funding and research invested in it. The benefits from inertial confinement fusion could outweigh the benefits from magnetic confinement fusion. The determining factor is the amount of energy needed to be recycled to produce the laser or ion-beam to initiate the reaction.

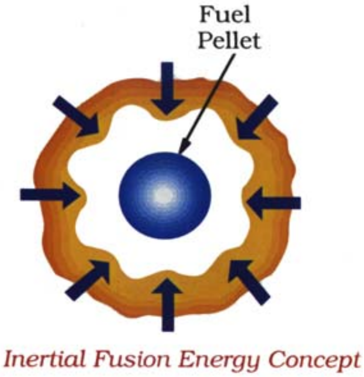

Figure 6: Inertial Confinement Fusion, Stage One (Courtesy of Princeton Plasma Physics Laboratory)

8.1 CONCLUSION

Nuclear fusion is a rapidly approaching technology that will have a significant impact on the lives of Mechanical Engineers graduating today[19]. Fusion power plants will seek to employ highly motivated and knowledgeable Mechanical Engineers to design power-generating systems. In order for today's students to be prepared for the tasks that await them, they must know the present state of fusion research and the possible future. The increasing energy shortage the world faces can be solved by nuclear fusion. Mechanical Engineers will help design the fusion power plants of tomorrow and aid the world in alleviating its energy woes.

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