Nuclear Fusion – Research Update

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CIBO Energy and Environmental Committee Meetings

Nuclear Fusion

- In Feb. 1970, I was assigned to the MIT School of Chemical Engineering Practice work station at Oak Ridge National Laboratories.
- My first project was to work on the design of a cooling system for a fusion reactor.
- Two coolant materials were under consideration:
  - Liquid Lithium
  - A molten salt of lithium beryllium fluoride, also known as “flibe”.
- Lithium was key to the cooling system, as energetic neutrons would react with the lithium to form helium and tritium. Tritium is fuel for the fusion reactor.

Nuclear Fusion

- The concern then was that nuclear fusion was 50 years away.
- Over the course of time, it seemed like fusion was still 50 years away and would continue to be so.
- Recently, researchers at Lawrence Livermore Laboratories announced a breakthrough in fusion reaction technology.
  - For the first time, more energy was released from a fusion reaction than was used to ignite it.
  - This ignition problem has been a key barrier to the advancement of fusion research for several decades.
- Thus, are we getting any closer?

Nuclear Fusion

- Fusion is the process that powers the stars.
- Hydrogen is “fused” into helium, liberating tremendous quantities of energy.
- Of course this all happens at millions of degrees in the sun.
- The question becomes how to control such a process to generate electricity here on earth.
- At high temperatures, the gas is a plasma (i.e. electrically charged).
- Prior work focused on magnetic confinement of the plasma.
- The current breakthrough used 192 lasers focused on a small amount of material in a process called inertial confinement.

Nuclear Fusion

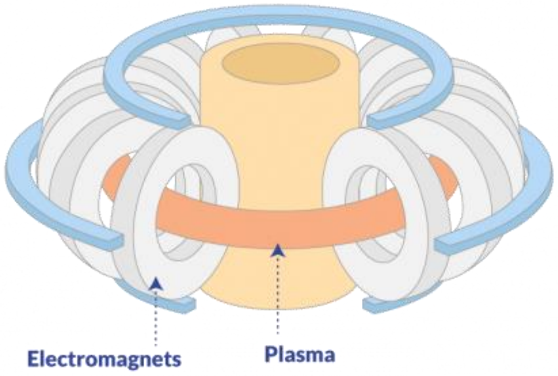
- The net energy gain achievement applied to the fusion reaction itself, not the total amount of power it took to operate the lasers and run the project.
- For fusion to be viable, it will need to produce significantly more power and for longer.
- One approach to fusion turns hydrogen into plasma, an electrically charged gas, which is then controlled by humongous magnets.
- This method is being explored in France in a collaboration among 35 countries called the International Thermonuclear Experimental Reactor (ITER), as well as by researchers at the Massachusetts Institute of Technology and a private company.

Nuclear Fusion

- The two approaches are shown schematically at right.
- The two systems still need a lot of testing and development in order to become sufficiently capable of generating electricity
- The RANE group forecasts availability after mid century.

Two Approaches to Fusion Energy

Compared with fission, fusion is safer, produces more energy and does not result in long-lived radioactive waste. Fusion can be achieved through two primary methods: magnetic confinement and inertial confinement. In 2022, the U.S. National Ignition Facility became the first group to achieve a positive energy gain (more power output than input) using inertial confinement.

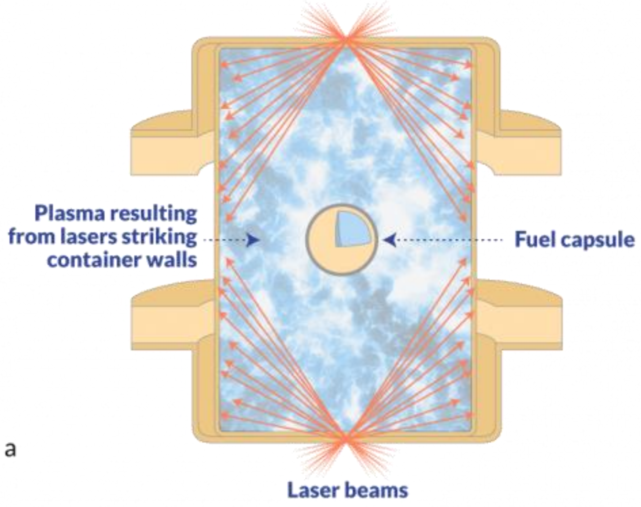


Magnetic confinement

- A current runs through charged electromagnets, creating (and containing) plasma from deuterium and tritium fuel.
- These energized plasma particles begin to heat the fuel plasma until fusion occurs, releasing great amounts of energy.

Inertial confinement

- Laser beams heat the wall of a gold capsule called a hohlraum, creating plasma and X-rays.
- The heat and pressure from the plasma and X-rays compress deuterium and tritium atoms contained in the hohlraum until they fuse to form helium, releasing great amounts of energy.
- That energy causes more atoms to fuse, resulting in a chain reaction and a sustained thermonuclear burn. The energy from the fusion burn is captured for output.



Source: IPP, NIF

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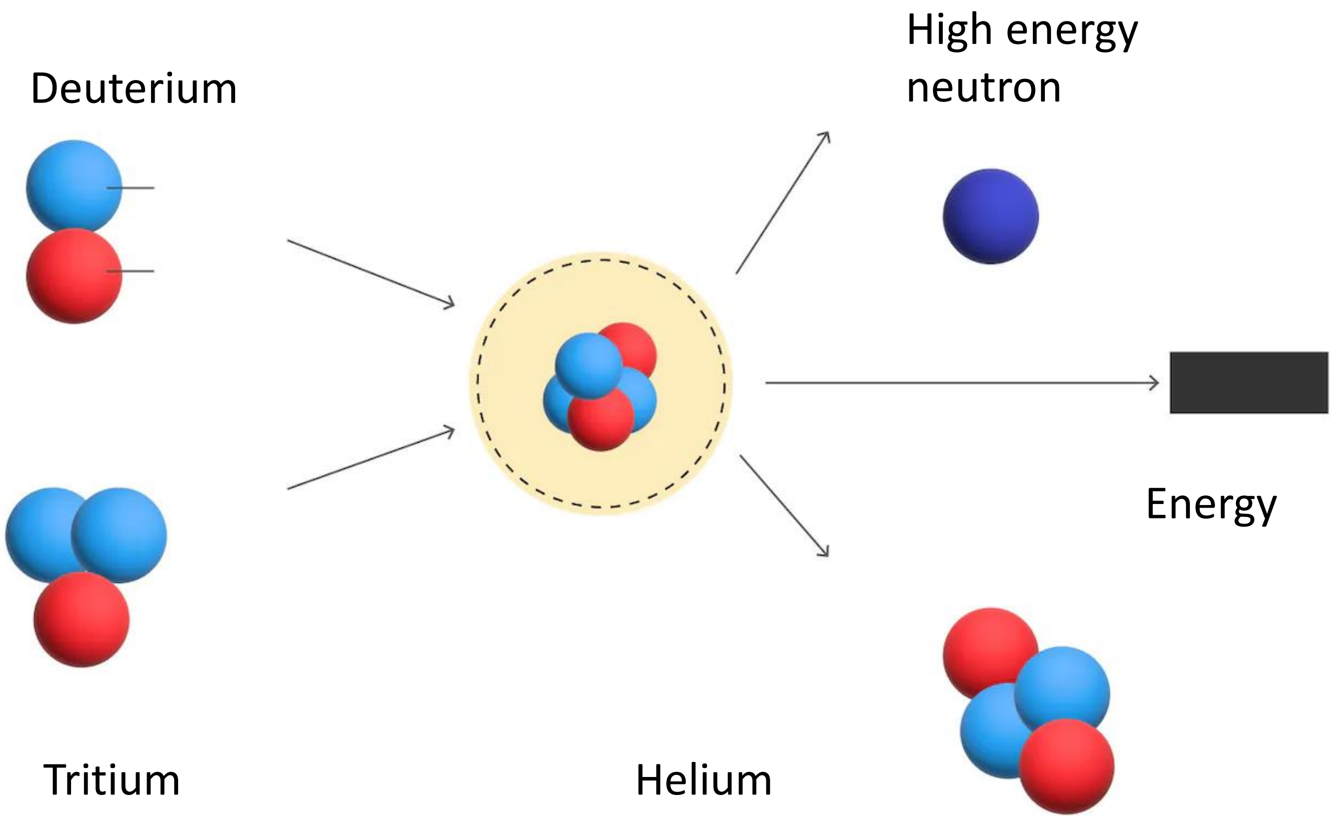
Nuclear Fusion

- The “D-T” reaction releases tremendous quantities of energy plus high energy neutrons.
- The high energy neutrons react with lithium to produce more tritium.
- Deuterium already exists in ordinary water.



Nuclear Fusion

- Perceived Benefits
  - Tremendous quantities of energy released from small amounts of materials.
    - Estimates are roughly 2*e11 BTU/lb of helium produced.
    - Hence the claims of "nearly limitless energy".
  - No radioactive waste is produced. The only by product is helium.
  - Essentially "fail safe".
    - You can't make a bomb from the feedstocks. A hydrogen bomb requires a fission bomb to first provide the energy to fuse the hydrogen. No atomic bomb….no hydrogen bomb.
    - The reaction is extremely hard to get started. Any power loss would cause the reactions to shut down.
  - Carbon free.

Nuclear Fusion

- That all sounds great, but how will actual electric power be produced when all of this equipment is actually working?
- The current favorite for cooling the system is flibe.
    - The flibe absorbs the highly energetic neutrons to create tritium.
    - In the process, it heats up.
- The hot flibe must now be transported to a steam generating vessel in much the same way that current fission reactors send their hot water to a steam generating vessel. The difference is that the flibe is not radioactive.
- The steam thus generated can now be sent to a steam turbine to turn a generator to make electricity.

Nuclear Fusion

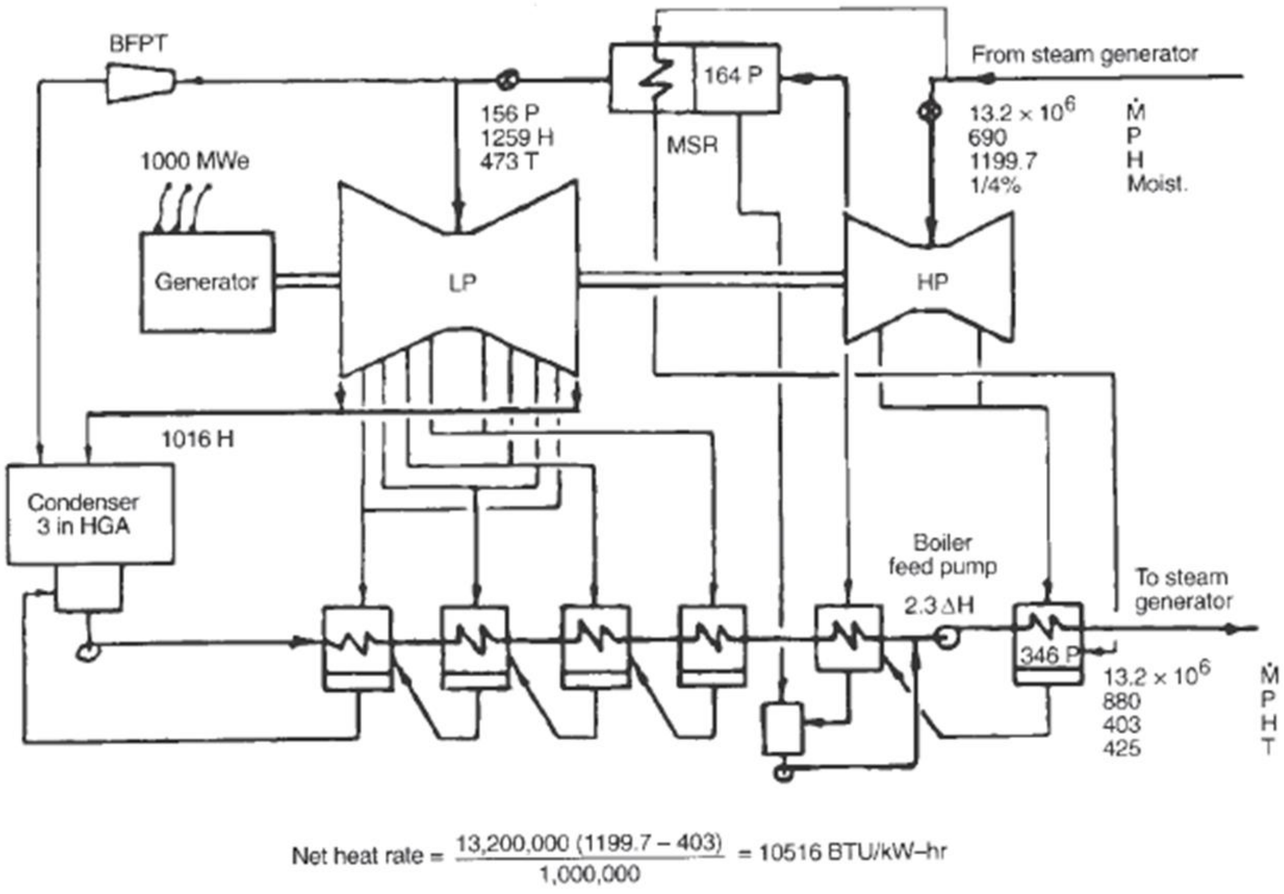
- The US DOE called me at home to ask about "drivers" for fusion power and how I would go about doing a "techno-economic analysis".
- Given the similarities between current fission power plants and what a fusion power plant might look like, I suggested that the DOE start with cost returns from a recent nuclear plant construction (i.e. Southern Company Plant Vogtle). This would form the basis for the plant cost estimate.
- The fission based equipment would be removed from the estimate and the fusion based equipment would then be added in. From there a first cut at a plant cost could be calculated.
- Then the analyst could examine what kinds of cost reductions might be needed to come up with a plant that could produce power at a reasonable cost per kwhr.

Nuclear Fusion

- This is a fission plant.
- The white stuff coming off the cooling towers is condensed water vapor and is not radioactive.
- The small building to the left of center houses the nuclear reactor.
- The rest of the equipment makes up the power plant.

Nuclear Fusion

- This is the steam turbine heat balance for a nuclear plant.
- Note that the steam pressure is low for a power plant (690 psia). Further the steam is essentially saturated steam at 500 F. There is no superheat.
- A portion of the high pressure steam is taken off and delivered to a moisture separator reheater to raise the temperature going to the LP turbine.



Nuclear Fusion

- Due to the saturated steam conditions, the heat rate is rather high.
- We can expect to need all of this equipment in a fusion plant, as saturated steam will be produced in the steam generator from the hot flibe.
- The nuclear steam turbine is a large device. As a result, the turbine rotates at 1800 rpm to avoid a tip speed greater than the speed of sound.
- As a result, a special generator is required that has 2 magnetic fields in order to generate 60 cycle power.
- There will need to be a helium recovery system as well as a tritium recovery system.
- All of this now has to be designed and integrated to work together to create a working fusion reactor system.

Nuclear Fusion

- ITER had hoped to begin operating a fusion plant by 2025. However, that has been delayed to at least the end of the decade and more likely the early 2030s.
- A spin off from MIT plans to build a fusion plant in Massachusetts by the end of the decade. It will likely be owned by the developers (which will drive up the COE due to the rate of return needed to pay for the plant).
- Let’s assume that these can actually be built and operated, at least for a period of time. A commercial plant would require performance guarantees as well as demonstrated operating time.
- The nuclear plant track record hasn’t been that great, starting with “too cheap to meter” and ending up with very expensive equipment.

Nuclear Fusion

- These test plants will have to be started up, tested, debugged, and operated for a period of time before anyone would even think of buying one for electric generation.
- Even small fusion plants will be big.
- A decent sized unit would have to demonstrate operation for over 1 year at a capacity factor of at least 70% or better.
  - That operation would have to be smooth (i.e. not needing constant baby sitting)
  - Any and all permit issues would have to be resolved.
- Finally, there is cost. We don’t really know what these things will cost and won’t know until we build one (at least at demonstration scale).

Nuclear Fusion

- Let's assume that we get one of these test units up and running in the 2030s.
- It will likely take 10 years of development to get to the point where we might expect a commercial offering, assuming everything went well.
- That would mean that the earliest we might be looking at a first commercial type fusion plant would be in the 2040s.
- That might be optimistic.
- Thus, we might forecast that fusion power is 25 – 30 years away. Even if we are ready for a commercial offering in the 2040s, it will take some time to get the plant built and put into operation. That gets us to the 2050s.

Questions?