Fuel Cell Submarine

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Introduction(Sam)

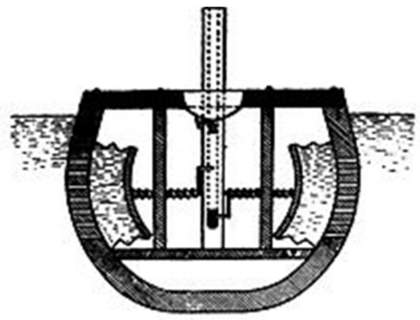
- Submarines are developed and refined primarily to gain an advantage in warfare but also for underwater explorations.

- William Bourne designed one of the first workable prototype submarines in 1578.

- Early submarines relied on human power for propulsion.

- Ictineo II, designed by Narcis Monturiol in 1864, was the first mechanically powered submarine using a steam engine.

- Electric powered submarines were developed in the 1880s.



Introduction Cont’d

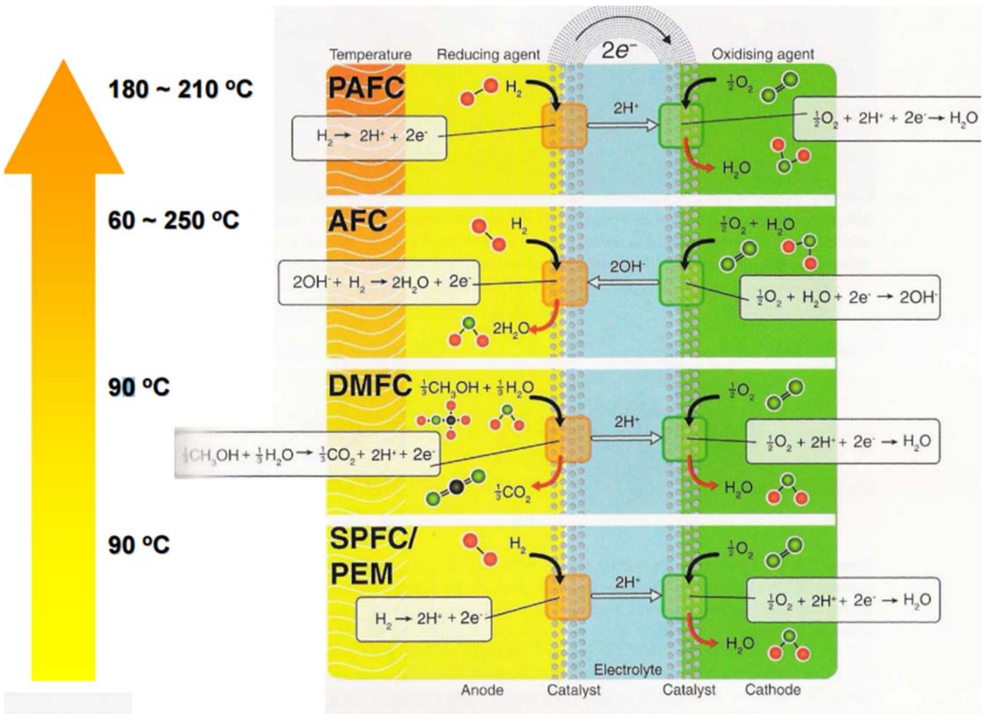
- In 1896, John Philip Holland designed the Holland Type VI submarine, which would become the first modern commissioned submarine of the US Navy.
- First introduction of the Diesel (internal combustion engine) Electric propulsion system.
- The system uses electric propulsion underwater, and uses a Diesel engine to recharge the batteries on the surface.
- Use of submarine snorkels was introduced in 1943, allowed for non-electric powered propulsion underwater
- The USN “nautilus” was the first nuclear-powered submarine to set sail in 1955, allowing submarines to remain submerged for much longer.
- The German Type 212 was the first submarines to use fuel cells for air-independent propulsion

Engineering Requirements (Sam)

- Ability to submerge for long periods of time: modern nuclear submarines spend around 70 days at sea between maintenance
- High mobility: modern submarines can reach speeds of 25+ Knots submerged
- Low noise to avoid detection
- Safety: Low flammability in case of emergencies.
- Environmentally friendly

Fuel Cell Requirements - Low Temperature (CT)

- PEMFC (Polymer Electrolyte Membrane)
- PAFC (Phosphoric)
- AFC (Alkaline)
- DMFC (Direct Methanol)



Fuel Cell Requirements cont'd (CT)

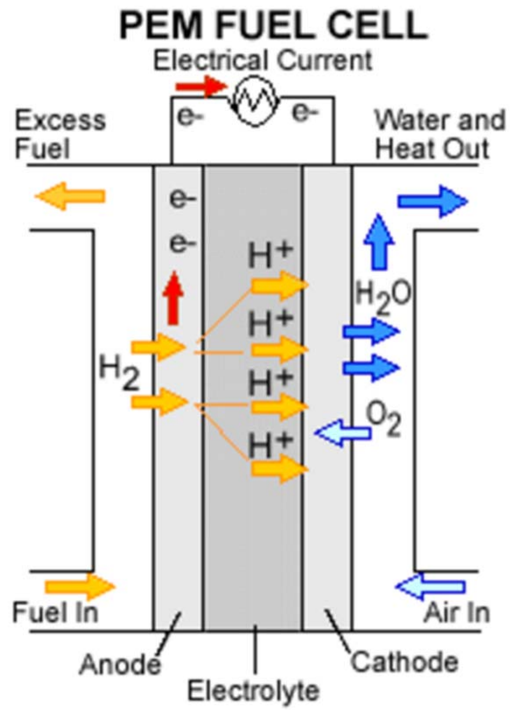
- Rule out PAFC (Phosphoric Acid)
  - Optimum efficiency is 180~210^{o}C
  - At 42^{O}C , acid starts to solidify
  - At 210^{O}C, phase transition starts losing abilities an electrolyte
  - Typically large and heavy, replenish corrosive electrolyte
- Rule out AFC (Alkaline)
  - Carbon dioxide poisoning - small amount can severely damage the system
  - Pure H_2 and O_2
  - Replenishment of KOH electrolyte

Fuel Cell requirements - PEMFC vs. DMFC (CT)

- Similar disadvantages, e.g. platinum catalyst, poor CO and S tolerance
- DMFC has much lower efficiency compared to PEMFC correlating to power density
- 30~100 mW/cm^2 vs 300~1000 mW/cm^2
- Advantages of PEMFC
  - Fast Start-stop
  - High power to weight ratio
  - Allows high compact design

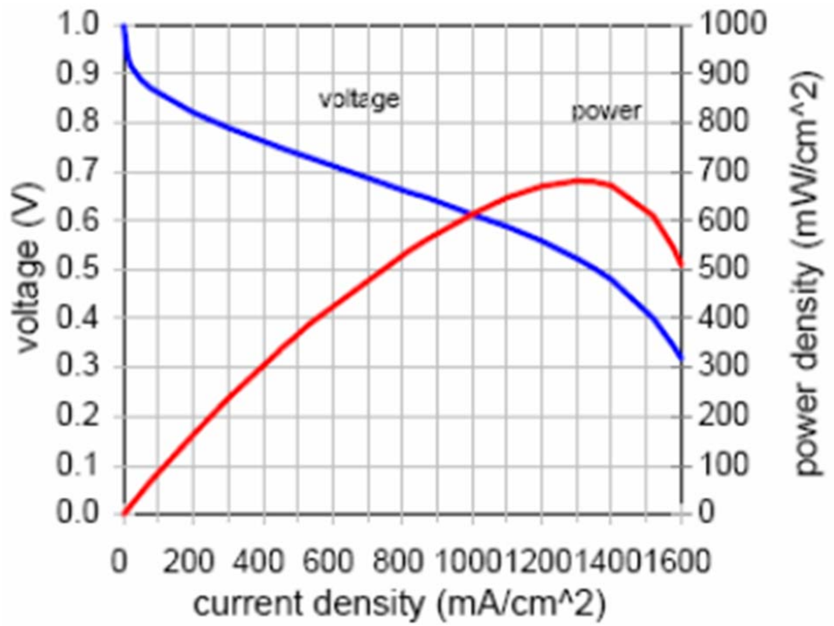
Electrochemical Reaction (CT)

- Anode : $2H_2 \rightarrow 4H^+ + 4e^-$
- Cathode : $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
- Cell: $2H_2 + O_2 \rightarrow 2H_2O$
- E_O= 1.23 volts



Operating Parameters for a 300 KW fuel cell (CT)

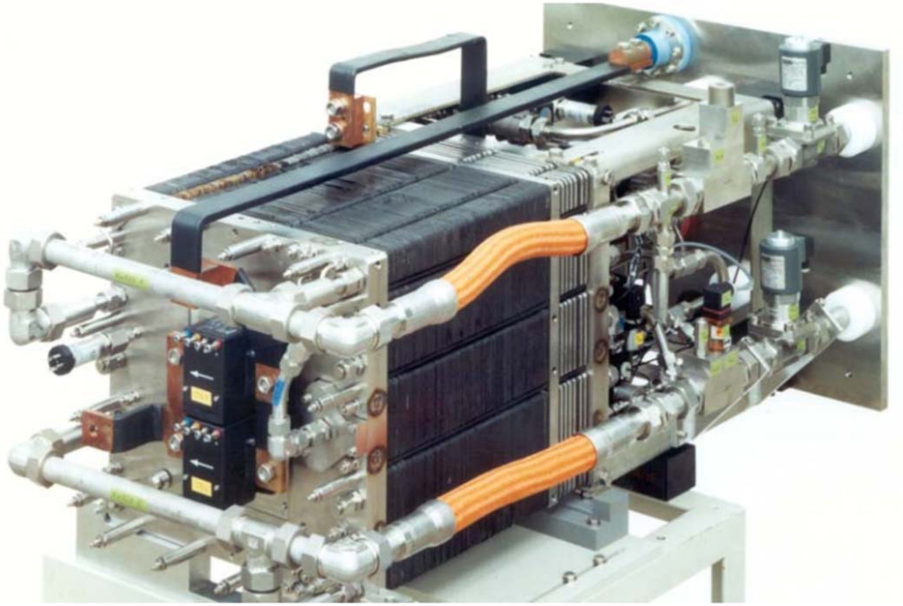
- Want to operate at max power
- .53 volt per cell
- 1300 mA/cm^2
- Assume 1 fuel cell has area of 100 cm^2
- Assume 1 fuel cell is 200 microns thick
- 25%-35% efficiency



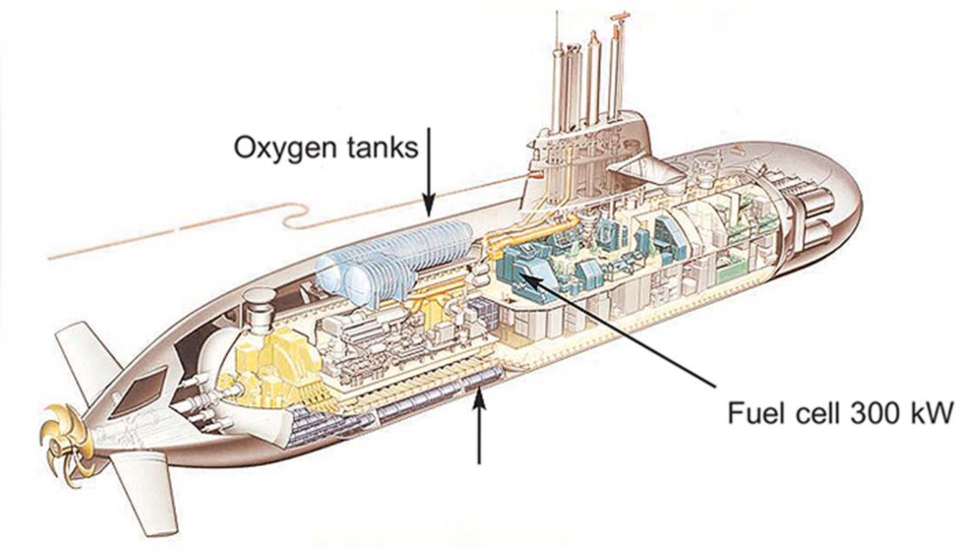
Calculations (CT)

- Current through cell? Current density x Area =1.3 A/cm^2 x 100 cm^2 = 130 A
- Total Voltage required? 300,000/130 = 2307.7 volts
- Number of cells stacked? 2307.7/.53 = 4354.14 cells
- Thickness of cells stacked? 200 microns x 4354.14 = .87 meters
- Very thin stack, but the Area makes up for the size
- Due to 25-35% efficiency, need 4 fuel cell stacks

34 KW PEMFC Fuel Cell in German Submarine (CT)

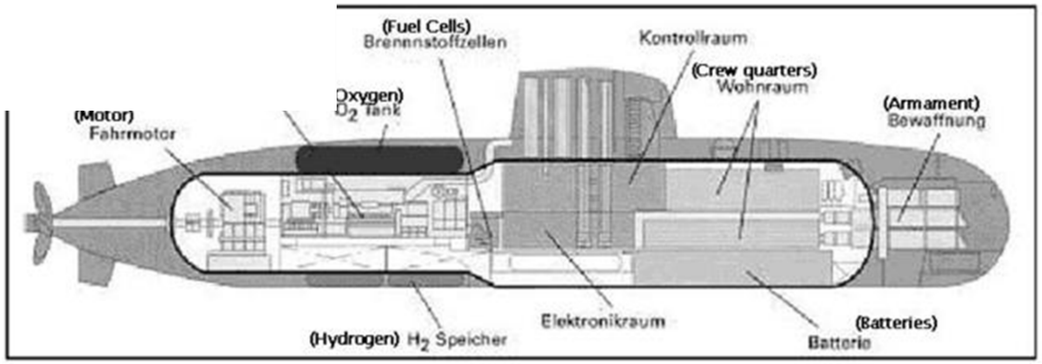


Detailed Design and Layout (TK)



Constraints:

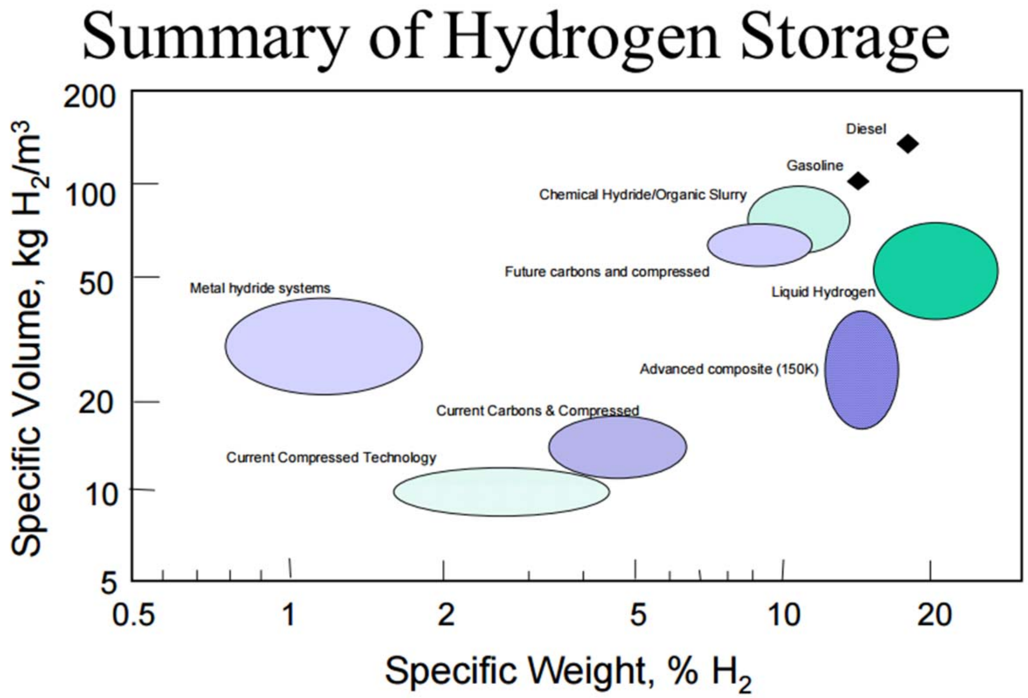
- Fuel Cells
- Fuel Storage



Detailed Design and Layout (TK)

Choosing Hydrogen Storage

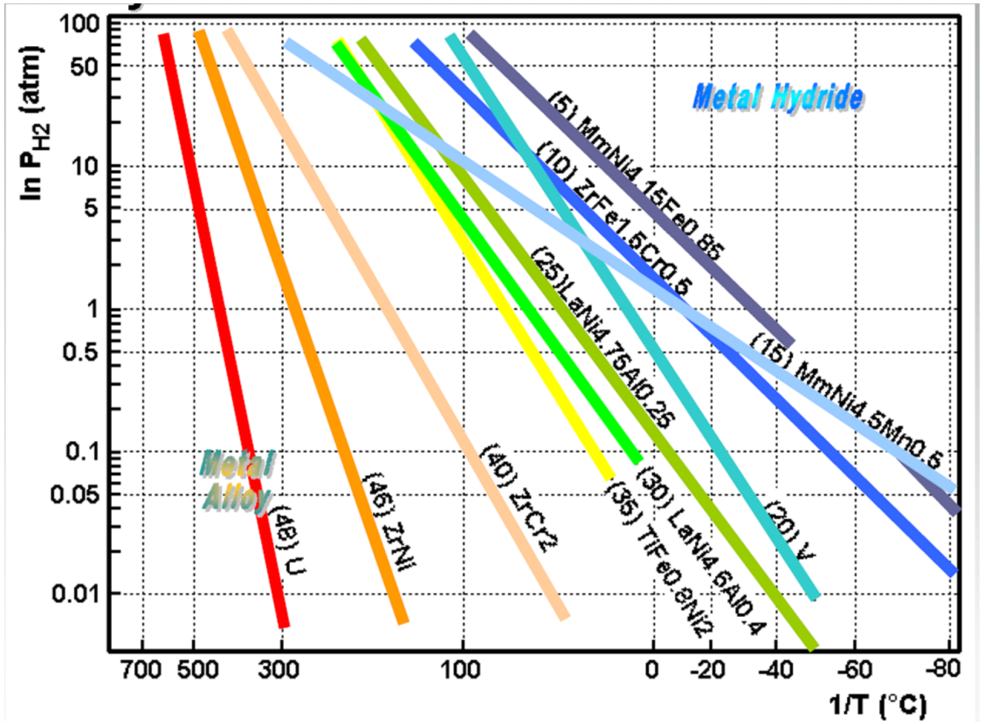
- Compressed Hydrogen
    - Requires high power compressors and heavy tanks to contain the pressure
- Liquid Hydrogen
    - Requires extremely low temperatures and impractical for underwater operations



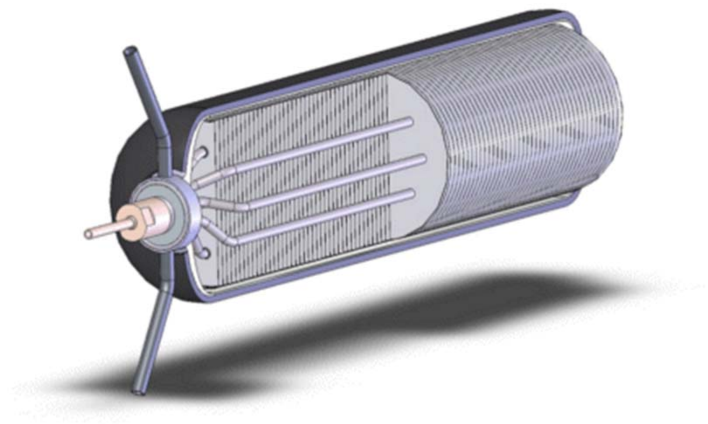
Detailed Design and Layout (TK)

Reversible Metal Hydrides (Chosen)

- While Metal Hydrides are a heavy option, it is the least costly and the safest method of storing hydrogen.
- By manipulating temperature and pressure, hydrogen gas can be absorbed or released at will



Detailed Design and Layout (TK)



Fuel Storage Specifications:

- 15 hydride tanks
- Each will weigh about 4 tonnes with a volume of 1200 litres.
- Will be able to provide 1 MWh of energy per tank.
- Metal hydride will be heated using waste heat from water cooling system or propulsion system to provide energy for endothermic dehydrogenation

Comparison with Other Submarines (Cost) (YJ)

- Nuclear Submarines
  - ~$2 billion per unit
  - ~$0.096 per kWh (US Energy Information Administration)
- Diesel Submarines
  - ~$500 million per unit
  - ~$0.20 - $0.30 per kWh
- Fuel Cell Submarines
  - ~$500 million per unit (likely to cost a similar amount as diesel submarines, as the differences between the costs of the fuel cell and diesel engine are negligible on the scale of $500 million)
  - ~$0.15 per kWh

Comparison with Other Submarines (Top Speed and Time Submerged) (YJ)

- Nuclear Submarines
    - According to the U.S. Department of Defense, the top speed of the submarines of the Nuclear Powered Los Angeles class is over 25 knots (46 km/h; 29 mph), although the actual maximum is classified. Some published estimates have placed their top speed at 30 to 33 knots
    - Nuclear Submarines can stay underwater almost indefinitely with electric current being used to convert water into breathable oxygen for the crew, and hydrogen being discharged overboard. Rather, food for crew is the limiting factor.
- Diesel Submarines
    - The Barbel Class Submarine, the US' last diesel submarine in service, had top speeds of 14 knots (26 km/h; 16 mph) surfaced, 12 knots (22 km/h; 14 mph) snorkeling, 25 knots (46 km/h; 29 mph) submerged
    - Traditional Diesel submarines used a hybrid engine. It ran on diesel while surfaced, and used it to charge batteries while underwater. The batteries could last around 36-48 hours.

Comparison with Other Submarines (Top Speed and Time Submerged)(YJ)

- Fuel Cell Submarines
    - The 1,840-ton German and Italian U 212-class submarines use nine PEM fuel-cell modules each nominally rated at 34 kilowatts, to yield a total of approximately 300 kilowatts (400 horsepower). With metal-hydride hydrogen storage, the system is predicted to yield 14 days submerged endurance
    - It has the ability to run up to eight knots on the fuel cells

Comparison with Other Submarines (Stealth) (YJ)

- Silent running
    - Silent running is a stealth mode of operation for naval submarines, for evasion of discovery by passive sonar. Nonessential systems are shut down, and speed is greatly reduced to minimize propeller noise.
    - Electric submarines have special "silent running" engines designed for optimum performance at reduced speed. They require less active cooling (further reducing noise), and were generally equipped with plain bearings rather than ball bearings.
    - Nuclear submarines run even more quietly, at very low speeds only, by turning off active reactor cooling during silent running. The reactor is then only cooled by natural convection from water.
    - The PEM fuel cell has no moving parts, and therefore fuel cell submarines generate the least noise.

Comparison with Other Submarines (Safety and Environment) (YJ)

- Environmental concerns
  - Diesel is non-renewable and produces greenhouse gases.
  - Nuclear is relatively environmentally friendly, but with "catastrophic risk" potential if containment fails, releasing fission products into the environment
  - The PEM fuel cell is completely environmentally friendly, with no greenhouse gas emissions.
- Safety
  - Diesel is a flammable fuel. Exposure to diesel exhaust results in health effects ranging from irritation of the eyes and nose, headaches and nausea, to respiratory disease and lung cancer.
  - Britain’s ministry of Defence reports that the safety of submarine reactors compares "poorly" with that of nuclear power stations, and there could be dangerous leaks of radioactivity.
  - The PEM fuel cell is safer, as hydrogen although inflammable has a higher diffusivity.

Other New Innovative Submarines (YJ)

- New Diesel-Electric Submarine
  - Can stay submerged for 3 weeks
  - Quiet form of propulsion
  - Uses a diesel engine when operated conventionally on the surface but, underwater, they are supplied with an oxidant (such as liquid oxygen)
  - Meant to eliminate and replace the remaining advantages of nuclear submarines

Possible innovations? (YJ)

- Nuclear + Fuel cell Submarine
    - Nuclear power is used to hydrolyse sea water into oxygen for crew to breathe, and hydrogen used to power a fuel cell

Expected Benefits (CT)

- Lower total cost of operations in long run
- More environmentally friendly (less greenhouse gas emissions)
- Better safety
- Lower charging time compared to diesel submarines
- Stealthier due to less noise from lack of moving parts

Possible Drawbacks (CT)

- Lower top speed
- Less time spent submerged compared to nuclear submarine

Summary/Conclusion (YJ)

- Fuel Cells are a new technology with large potential for future research, development, and improvement
- Fuel Cell submarines have large advantages over nuclear submarines in terms of cost and environmental benefit, although it may have drawbacks in certain areas such as time spent submerged, which may be quintessential to military operations
- Even so, Nuclear - Fuel Cell hybrid submarines could conceivably combine the advantages of both fuel systems. E.g. Nuclear submarine that switches to fuel cell during silent running