Unmanned Underwater Vehicles

NPRE 470
Team B
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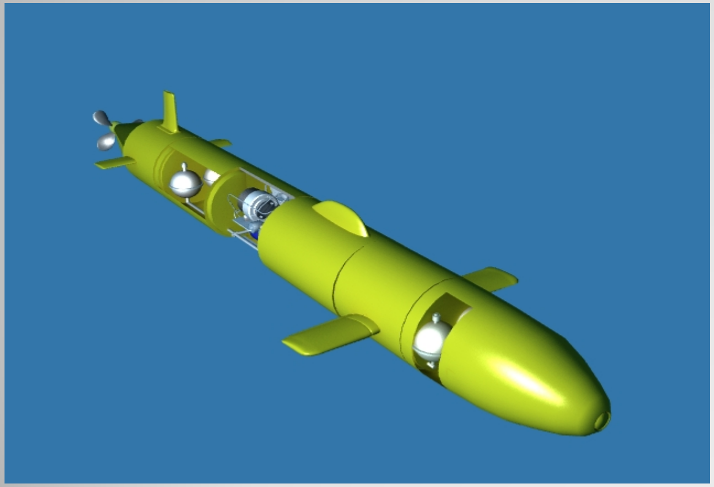
Bluefin-21 BP autonomous underwater vehicle AUV

What Is Unmanned Underwater Vehicles (UUV)?

- UUV is a robot vehicle that can operates underwater without an occupancy of human being, which commonly used in industries and in military.



UUV History

- UUVs were first developed in 1957 by Stan Murphy and Bob Francois at the University of Washington’s Applied Physics Laboratory.

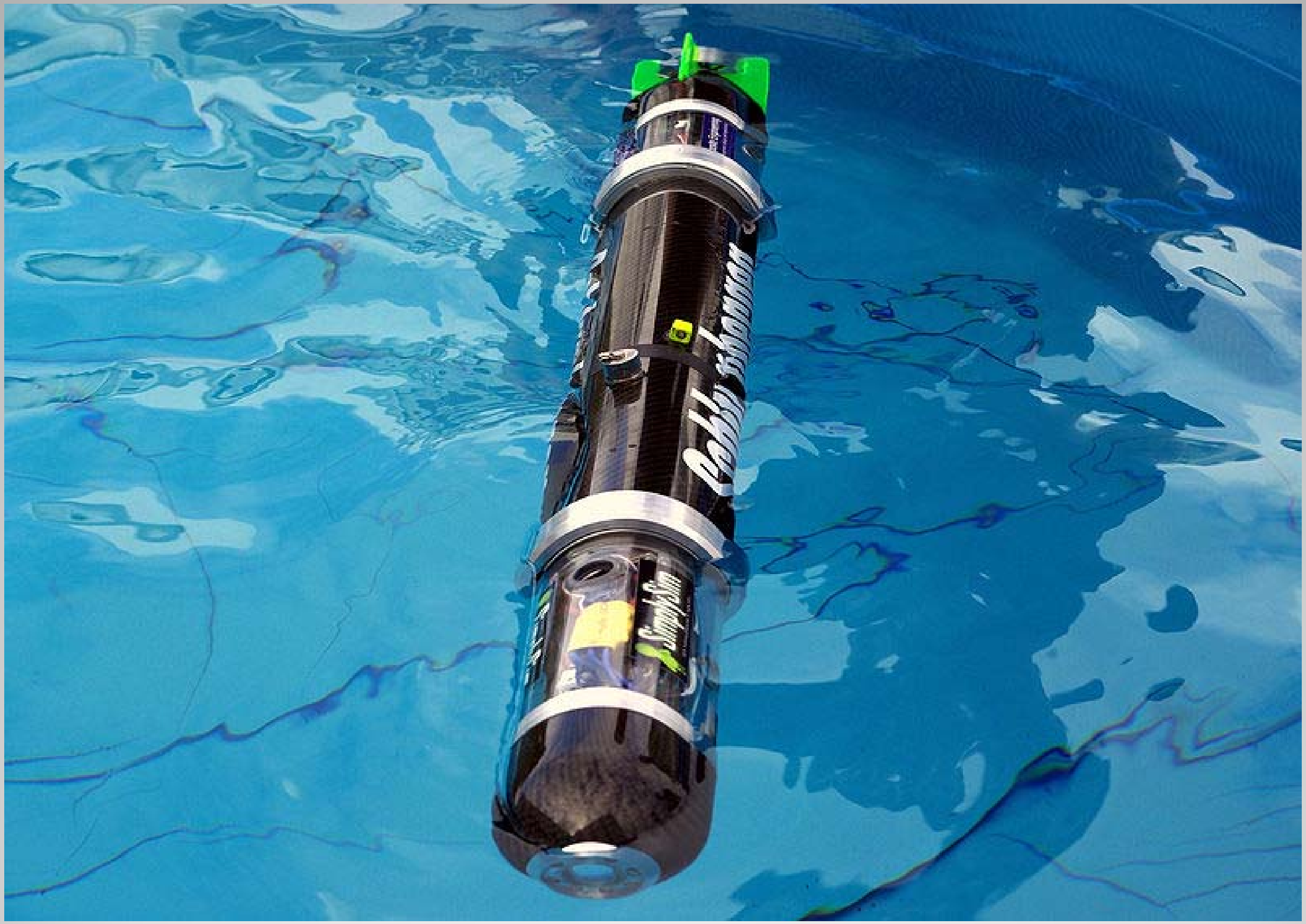
- UUVs were then further developed by researchers at MIT in the 1970s

UUV Classification

- UUVs can be split into two groups: AUVs and ROVs.
- Remote Operated Underwater Vehicles (ROVs): controlled from above water by a human operator via remote control or a tether cable
- Autonomous Underwater Vehicles (AUVs): operates robotically underwater without direct human input.

ROV

AUV



Application of Unmanned Underwater Vehicles

- **Commercial**

Oil and gas industry uses UUV to make surveys or detailed maps of the seafloor before starting to build subsea infrastructure.

- **Military**

UUV is used as a surveillance to detect any weaponry hazards such as mines and as reconnaissance for any possible hazardous objects.

- **Science**

UUV is used as a tool to study underwater ocean, such as collecting certain samples, measuring and determining various aspects including concentration, light intensity, microscopic life.

Size Range of Unmanned Underwater Vehicles

Class	Diameter (inches)	Displacement (lbs.)	Endurance High Hotel Load (hours)	Endurance Low Hotel Load (hours)	Payload (ft^3)
Man-Portable	3 - 9	< 100	< 10	10 - 20	< 0.25
LWV	12.75	~ 500	10 - 20	20 - 40	1 - 3
HWV	21	< 3,000	20 - 50	40 - 80	4 - 6
Large	> 36	~ 20,000	100 - 300	>> 400	15 - 30 + External Stores

Figure 5-1. UUV Classes

Reference: The Navy Unmanned Undersea Vehicle (UUV) Master Plan. Department of the Navy

Designing UUV

- Roles in these fields usually have similar design and operate in cruise mode with propeller thruster being the most common.

- The type of energy source selected for these applications is driven primarily by mission requirements for speed and endurance.

Requirement for UUV

- Long endurance
- High hotel or payload power
- High speed

These factors require increased energy capacity on UUV. Thus, UUV should have large energy storage feasibility to give high performance capabilities within a given mission.

Components of UUV

- **Military Components**
  - Missile Launcher
  - GPS
  - Subsea Weapons
  - Detection Sensors (Obstacles and enemies detection)
  - Communication System (RF)
- **Standard Components**
  - Pressure Sensors
  - Cameras
  - Batteries
  - Wireless Ethernet
  - Underwater Acoustic Positioning System
  - Propellers

Factors to consider for selecting Fuel Cell type for UUV

- Cost
- Energy Density
- Maturity of Technologies
- Safety
- Hydrogen Storage
- Product Life-Span
- Size
- Duration of Start-Up Procedures
- Efficiency

Possible Energy Sources

- Silver Zinc Rechargeable Batteries: only last for 14-17 hours, and take over 30 hours to recharge
- Disposable lithium-thionyl-chloride packs: Allow long term missions, but cost $100,000 each mission and and are very expensive to dispose of
- Diesel Engine: Cannot carry enough fuel for long-term missions
- SOFC and PEMFC Fuel Cells: The best of these four options

Possible Energy Sources

Feature	Baseline (rechargeable Ag-Zn battery)	Baseline (non-rechargeable Li-ion battery)	Pre-commercial InnovaGen® Fuel Cell Power System	Navy goal for 21" UUV Power
Weight	460 lbs	337 lbs	460 lbs	462 lbs
Reach, nmi 1-way @ 4 kts	30 nmi	103 nmi	120 nmi	120 nmi
Endurance High hotel load Low hotel load	10-15 hrs	57 hrs 64 hrs	50 hrs 70 hrs	20-50 hrs 40-80 hrs
Energy capacity	17-25.5 kW-hrs	96.5 kW-hrs	123 kW-hrs (14,000 kW-hrs)*	100 kW-hrs
Specific Energy	50 Whr/lb	200 Whr/lb	268 Whr/lb	200 Whr /lb
Cost	$1000 /kW-hr	$1000 /kW-hr	$100 /kW-hr*	<$1000/kW-hr

Possible Energy Sources

Comparison of Fuel Cell Technologies

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	< 1kW–100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10–100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	700-1000°C 1202-1832°F	1 kW–2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

For More Information

More information on the Fuel Cell Technologies Program is available at *http://www.hydrogenandfuelcells.energy.gov*.

Reference: U.S. Department of Energy, Energy Efficiency & Renewable Energy

Possible Energy Sources

Table 1. Energy density of UUV power source technology

Power source	Gravimetric energy density (Wh kg^{-1})	Volumetric energy density (Wh l^{-1})	Notes
Silver–zinc battery[a]	81	174	Good energy density but expensive, often used for specialist applications. Limited cycles
Lead–acid battery[b]	35	53	Low energy density but proven technology
Lithium ion battery[c]	128	315	Currently the most advanced rechargeable battery type
Direct borohydride fuel cell (solid fuel)	950 (operating at 50% efficiency)	2850	Technology still in the development phase. Fuel and products easy to handle. Increasing stealth over the DMFC
Direct methanol fuel cell (neat methanol)	690 (operating at 30% efficiency)	2070	A more developed technology than the DSBFC with good energy density, but the gaseous product would reduce stealth if released or would need additional hardware to dissolve gas before release.
PEMFC (H_2 fuelled)	690 (operating at 50% efficiency)	2070	Technology well developed, but would need a hydrogen source, reducing the volumetric energy density due to low hydrogen storage capacity

Comparison of Different Energy Systems

Table 2. Size, Payload, and Cost of 26.5" Diameter Systems for 500 W Hotel

SYSTEM	LENGTH (in)	WEIGHT (lb)	PAYLOAD		COST		
			Volume (ft^3)	Weight (lb)	Initial ($K)	Total Operational Cost ($ per run)	Expendables ($ per run)
Turbine hybrid	184	2666	10	1093	200	3570	165
SI hybrid	161	2144	10	1145	107	1630	126
Diesel hybrid	145	1788	10	1174	99	1790	91
PEM fuel cell	118	1220	10	1190	106	3170	172
Alkaline battery (D-cell)	85	1185	10	500	54	7550	6800
$LiSOCl_2$, BrCl (D-cell) (min. volume)	62	436	10	820	77	42,250	41,500
$Li/SOCl_2$ (D-cell) (min. cost)	87	697	10	1082	67	20,250	19,500
Silver/zinc rechargeable battery	78	883	10	720	80	4500	15

Operating at : 200V, $10ft^3$ volume, 500lb payload weight, capable of going 300 nm at its optimum speed, 500W Hotel load

Why Solid Oxide Fuel Cell ?

ADVANTAGES

- **Fuel Flexibility**
  - Pure H_2 is not necessary
  - Sulfur-resistant fuel cell type
  - Are not poisoned by CO, but used as fuel
  - Internal reforming of hydrocarbon fuels to yield hydrogen
  - Fast refueling of fuel
- **High Temperature(Around 1,000ºC)**
  - Removes the need for precious-metal catalyst
  - High Temperature Limits SOFC utilization to only large UUVs
- **High Fuel Efficiency**
  - 50-60% efficient at converting fuel to electricity
  - Utilizing high-quality waste heat(cogeneration), efficiencies could reach 90%
- **High Energy**
  - Power Density of 250-300 mW/cm^2,
  - Power Range of 1kW – 2kW
- **Solid Electrolyte**
  - Utilize hard, non-porous ceramic compound
  - Cells do not have to be constructed in the plate-like configuration
  - Fast reaction kinetics at electrodes

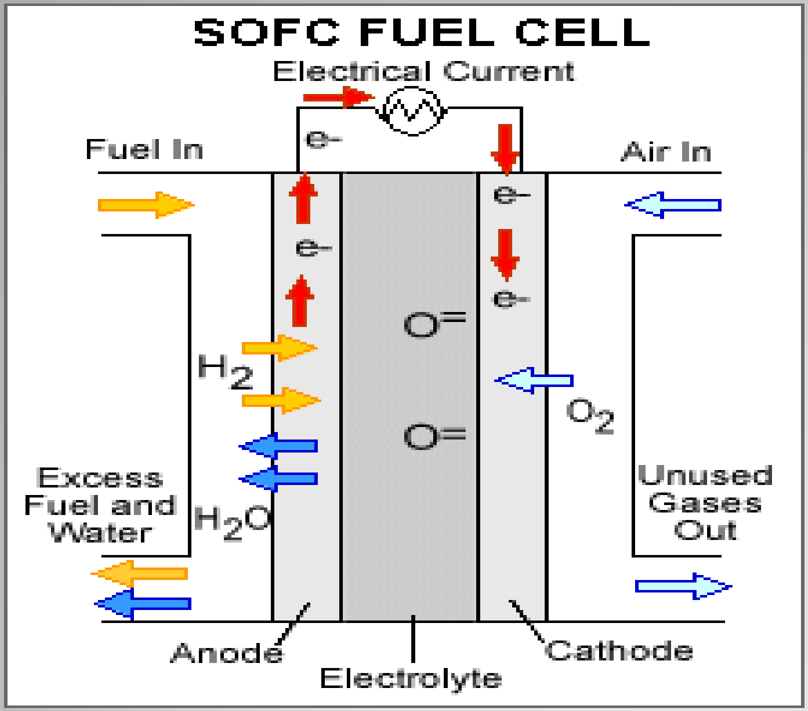
Why Solid Oxide Fuel Cell ?

DISADVANTAGES

- **High Temperature(Around 1,000°C)**

  - Significant thermal shielding required to retain heat
  - Expensive, high durability materials required at fuel cell
  - High Temperature Limits SOFC utilization to only large UUV

SOFC



Anode Half Reaction

$$H_2 + O^{2-} \rightarrow \; 2e^- + H_2O$$

Cathode Half Reaction

$$\frac{1}{2}O + 2e^- \rightarrow O^{2-}$$

SOFC Overall Reaction

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

Electrolyte Charge Carrier

$$O^{2-}$$

Why Polymer Electrolyte Membrane Fuel Cell ?

ADVANTAGES

- **Low Temperature(Around 80°C)**
  - Low temperature operation allows for a quicker startup (less warm-up time)
  - Low temperature allows for use in small/midsized UUVs
- **High Fuel Efficiency**
  - Theoretical Efficiency of 83%, but Activation Loss and Ohmic Loss lower this
  - Realistically, 40-60% efficient at converting fuel to electricity
- **High Energy**
  - Power Density of 250-350mW/cm^2 (Larger than SOFC value)
  - Power Range of 1kW – 100kW
- **Solid Electrolyte**
  - Cells do not have to be constructed in the plate-like configuration
  - Fast reaction kinetics at electrodes
  - Reduces corrosion and Electrolyte management problems

Why Polymer Electrolyte Membrane Fuel Cell ?

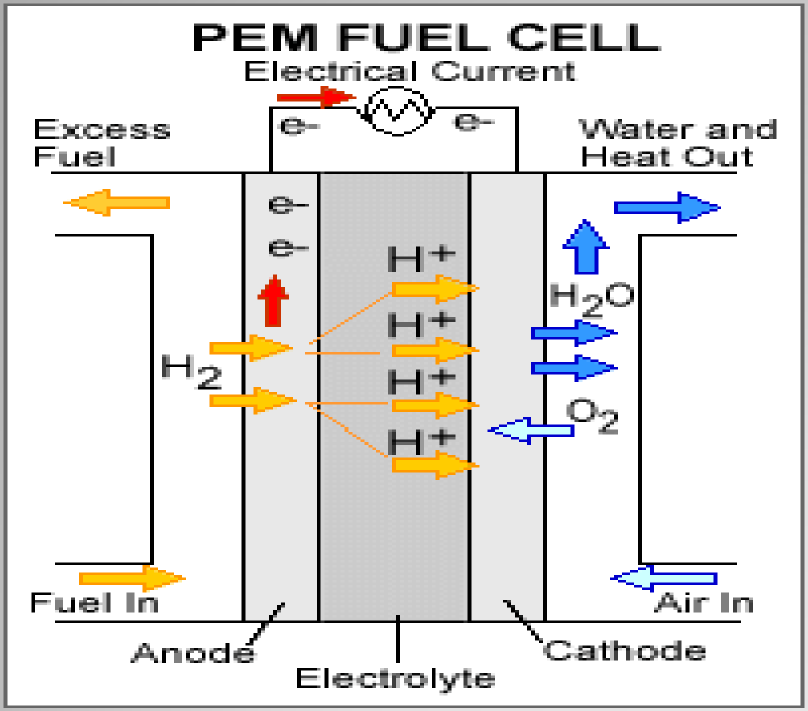
DISADVATAGES

- **Hydrogen Storage**

- Must store hydrogen on-board as a compressed gas in pressurized tanks

- Hydrogen has a low-energy density making it difficult to store enough hydrogen on-board to allow UUV to travel the same distance as gasoline-powered vehicles before refueling

PEMFC



Anode Half Reaction

$$H_2 \rightarrow 2H^+ + 2e^-$$

Cathode Half Reaction

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

PEMFC Overall Reaction

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

Electrolyte Charge Carrier

$$H^+$$

Why Direct Methanol Fuel Cell ?

- **Subcategory of PEMFCs**

  - Share same advantages and disadvantages as PEMFCs

- **Main advantage is ease in transporting methanal**

  - Makes DMFCs attractive to portable applications (ie. UUVs)

Why Alkaline Fuel Cell ?

ADVANTAGES

- **Low Temperature(Around 100°C)**
  - Low temperature operation allows for a quicker startup (less warm-up time)
  - Low temperature allows for use in small/midsized UUVs
- **High Fuel Efficiency**
  - Realistically, 60-70% efficient at converting fuel to electricity
- **High Energy**
  - Power Density of 250 mW/cm^2
  - Power Range of 10kW – 100kW
- **Cathode Reaction Faster in Alkaline electrolyte**
  - This increase in speed leads to higher performance

Why Alkaline Fuel Cell ?

DISADVANTAGES

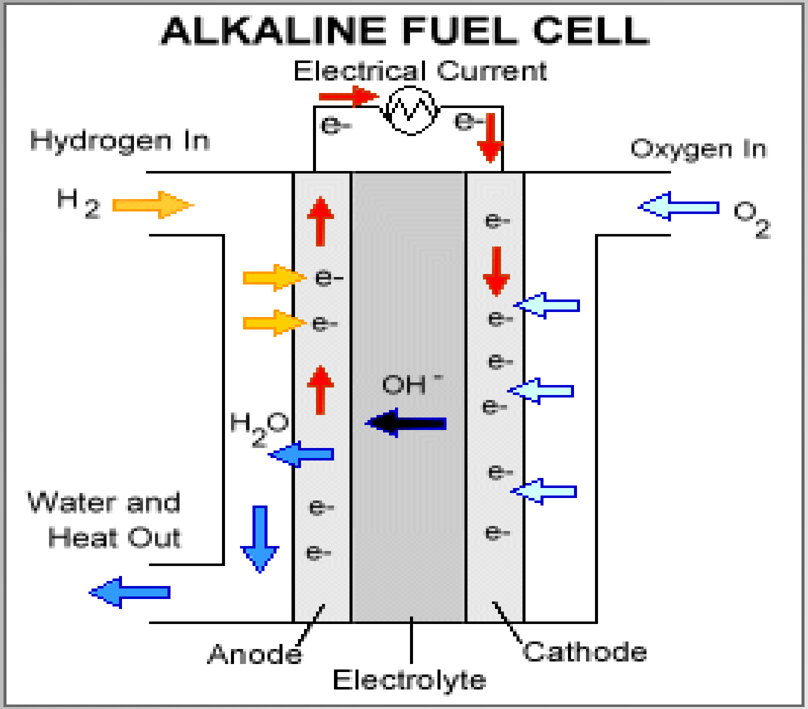
- **Carbon Dioxide Poisoning**

  - A small amount of CO^2 can affect this AFC’s operation

  - Purification of both hydrogen oxygen used in the cell required

  - This purification process is very costly, making AFCs unappealing for UUVs

AFC



Anode Half Reaction

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$$

Cathode Half Reaction

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

AFC Overall Reaction

$$2H_2 + O_2 \rightarrow 2H_2O$$

Electrolyte Charge Carrier

$$OH^-$$

Direct Borohydride Fuel Cell ?

- **Subcategory of AFCs**
  - Share same advantages and disadvantages as AFCs

- **Relatively new type of fuel cell that has been developed**

- **High operating efficiency makes it attractive for UUV use**

Cathode: $2O_2 + 4H_2O + 8e^- \rightarrow 8OH^-$ ($E^0 = +0.4V$)

Anode: $NaBH_4 + 8OH^- \rightarrow NaBO_2 + 6H_2O + 8e^-$ ($E^0 = -1.24$ V)

Total E^0 = +1.64V

Why Phosphoric Acid Fuel Cell ?

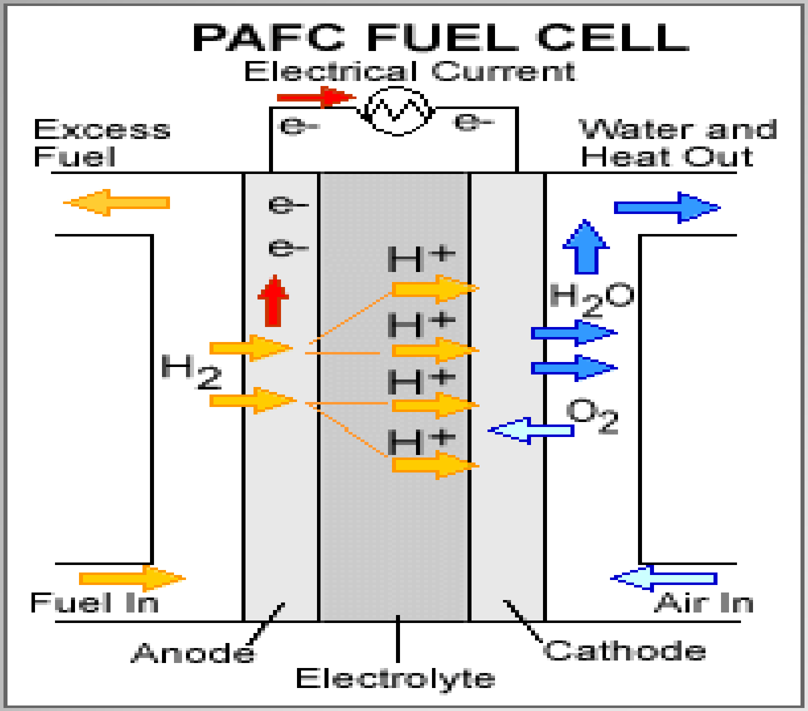
- **NOT Suitable for UUVs**

  - PAFCs are less powerful than other fuel cells, compared by weight and volume

  - As a result, these PAFCs are typically large, heavy, and stationary

  -This makes PAFCs unappealing for UUV application

PAFC



Anode Half Reaction

$$2H_2 \rightarrow 4H^+ + 4e^-$$

Cathode Half Reaction

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

PAFC Overall Reaction

$$2H_2 + O_2 \rightarrow 2H_2O$$

Electrolyte Charge Carrier

H^+

Why Molten Carbonate Fuel Cell ?

ADVANTAGES

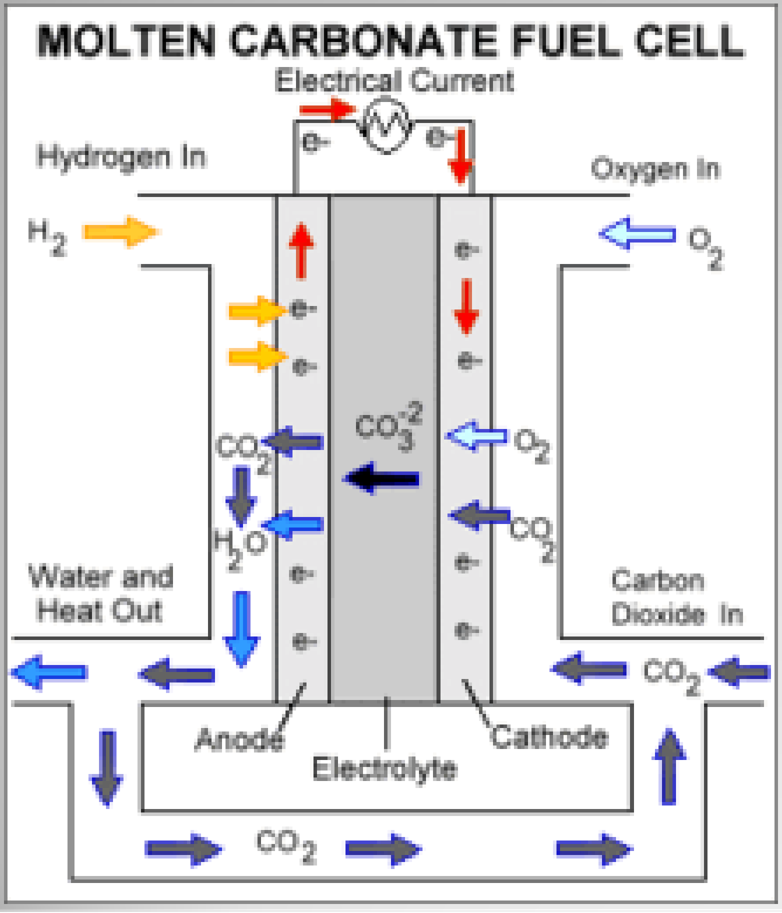
- **High Temperature(Around 650^{o}C)**
  - Non-precious metals can be used as catalysts, reducing costs
- **High Energy**
  - Power Range of 300kW – 3MW
- **Not prone to carbon monoxide or carbon dioxide poisoning**
  - They can even use carbon oxides as fuel

Why Molten Carbonate Fuel Cell ?

DISADVANTAGES

- **High Temperature**
  - Extremely high temperature of the MCFC causes a long startup time
  - High temp. and corrosive electrolyte used cause breakdown and corrosion
  - This decreases cell life, making MCFCs unappealing for UUVs

Molten Carbonate Fuel Cell



Anode Half Reaction

$$CO_3{}^{2-} + 2H_2 \rightarrow H_2O + CO_2 + 2e^-$$

Cathode Half Reaction

$$CO_2 + \frac{1}{2}O_2 + 2e^- \rightarrow CO_3{}^{2-}$$

MCFC Overall Reaction

$$2H_2 + \frac{1}{2}O_2 \rightarrow 2H_2O$$

Electrolyte Charge Carrier

$$CO_3{}^{2-}$$

Fuel Cell Choice

- Based on advantages and disadvantages of these 7 types, SOFCs, PEMFCs, DBFCs, and DMFCs are the best fuel cell choices for UUVs.

- All four share the characteristics of high fuel efficiency, high power density, mobile, and can endure long missions without refueling.

- SOFC is more suitable for large UUVs
- PEMFC more suitable for small and midsized UUVs

Future Design I

- Major Challenges: Reliability for multiple thermal cycles, thermal management in the closed system.
- SOFC has higher efficiency than conventional PEMFC
- Steam reformer in DOE design also requires large amount of heat.

Future Design II

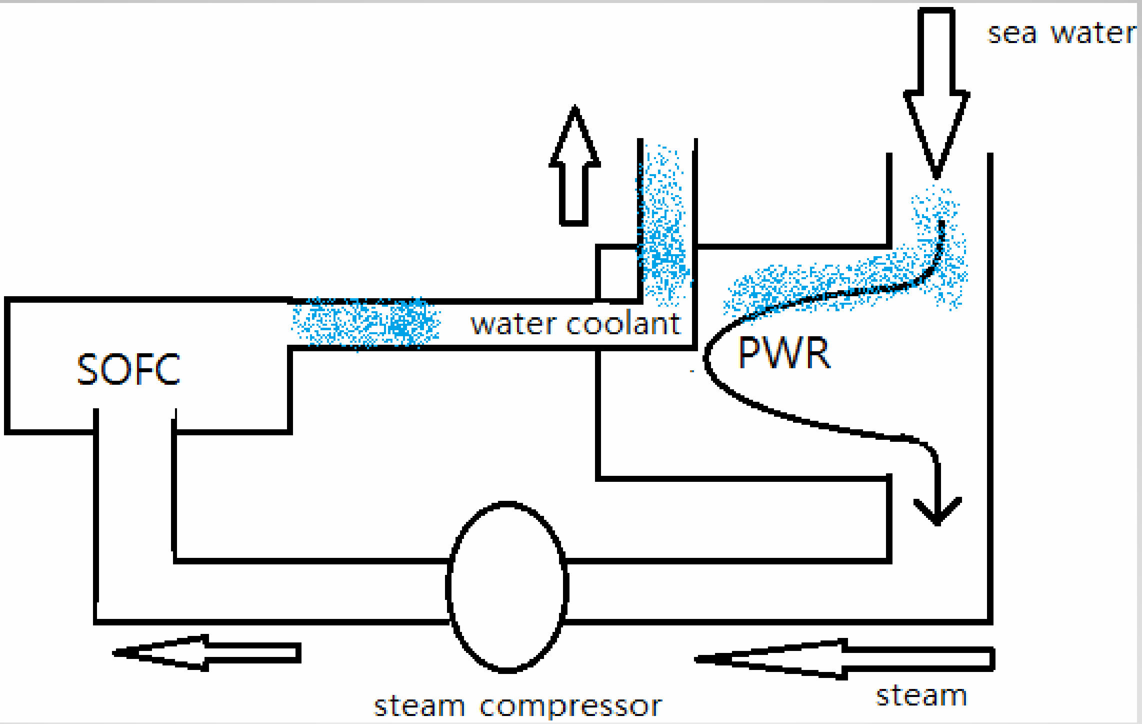
- Resolution for heat management
- Conventional SOFC can bring the power up to 2MW, while current submarines may require power up to 3.5MW
- Nuclear waste regarding warmed water

Future Design III

- Warm water or steam from PWR can be used as heat source for SOFC
- Temperature difference between output steam from PWR and required temperature for SOFC.
- Introduction of steam compressor

Future Design IV

- Design



Future Design V

- $pv = nRT$; $T = \frac{pv}{nR}$; for steam compressor
- Compression Cost:

Compressor constantly puts steam into fixed volume to increase the pressure

For directly proportional pressure change, $T \propto p$;

$$T_{input} = 316^{o}C,\ T_{out} \geq 1000^{o}C$$

$$\text{Compression Work} = \frac{\text{Pout}}{\text{Pin}} \geq \frac{1000}{316} = 3.165$$

$$\text{Annual Cost} = \$859{,}836$$

Future Design VI

Tab.1 – FC Performance and Use

		PEMFC	SOFC	MCFC	DMFC
Operating Temp. (°C)		80-150	800-1,000	>650	80-100
Fuel		H_2	H_2, hc	ng, hc	methanol
Electrical Effic. (%)		35-40	<45	44-50	15-30
Applications		FCV Power	Station. Power	Station. Power	Portable Power
Lifetime (h)	FCV	2,000	6,000	8,000	na
	Power	30,000	20,000	20,000	
Target lifetime (h)	FCV	4,000	40,000	40,000	
	Power	20,000	60,000	60,000	na

Future Design VII

- Cost and Benefits (cost based on Stack)
  - Pressurization:
    - Compression + Leakage Prevention cost = $195,384+$895,836 = $1,091,220
    - Conventional Temperature Management Cost = $154,510
  - Power generation and production cost (based on Mass production)

    Net benefit: $(PEMFC-SOFC) - Pressurization Cost = ($100/kW-$335/kW) - $18/kW + $4/kW= -$249/kW
    Net lifetimes: (SOFC-PEMFC) = 4000~36000 hours
    Benefit by lifetime increment = $35,520,000/year

    - Total Benefit: $34,085,760/year in 2010 dollars.

➢ Average annual cost: $600,000,000/year in 2010 dollars.

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Question and Answer