



Rechargeable Cryogenic Reactant Storage and Delivery System for Fuel Cell Powered Underwater Vehicles

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**Autonomous Underwater Vehicles 2002
Workshop on AUV Energy Systems
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INTRODUCTIONS

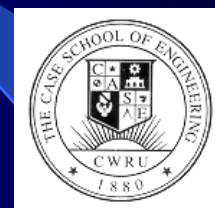
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PRESENTATION OUTLINE

- **UUV LOX SYSTEM DESIGN**
- **SYSTEM DESIGN TOOL**
- **PRE-HAZARD ANALYSIS**
- **BENEFITS OF LOX**
- **CRYOGENIC FLUID MANAGEMENT OPTIONS**
- **SUMMARY**



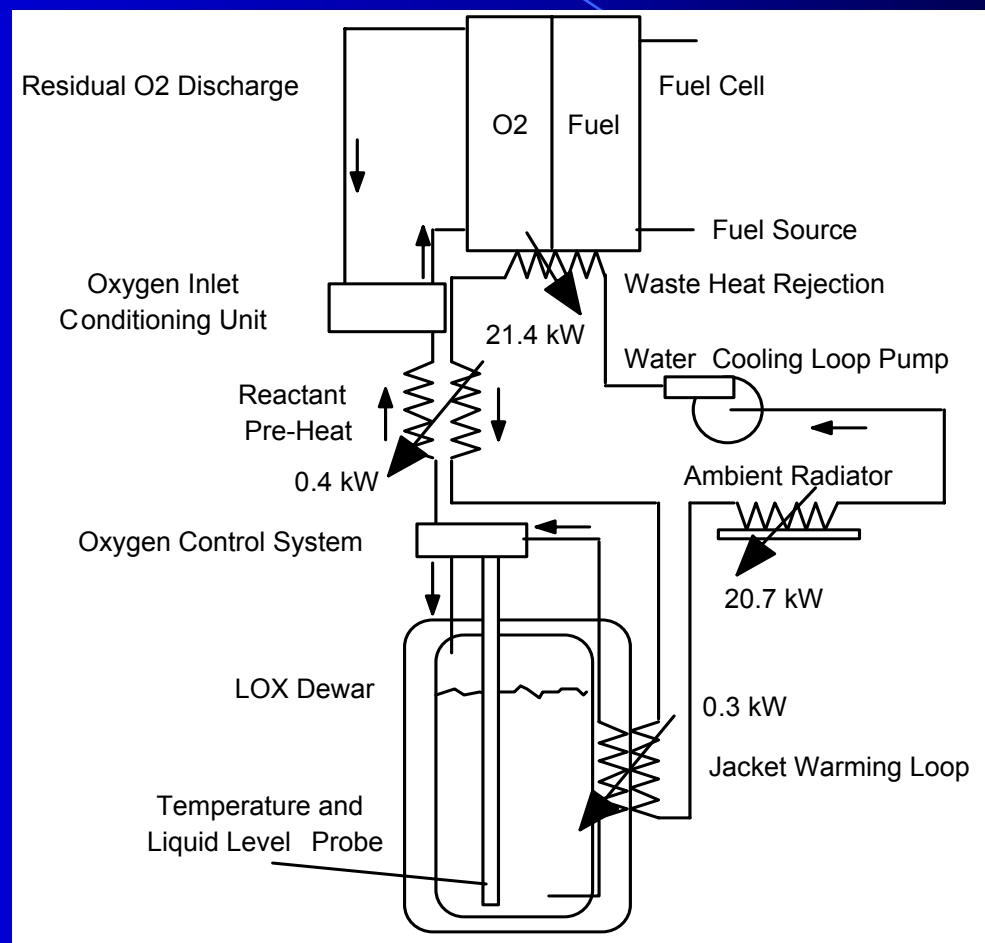


UNMANNED UNDERWATER VEHICLE (UUV) OXYGEN SYSTEM DESIGN REQUIREMENTS

- **50 kg OXYGEN STORAGE**
- **OXYGEN FLOW RATES 0.1 TO 100 gm/min**
- **VOLUME CONSTRAINTS OF MARK 48 TORPEDO**
- **HIGH DEGREE OF SAFETY**
- **MINIMIZE HOST VEHICLE OPERATIONS**
- **RAPID TURN AROUND TIMES**



Unmanned Underwater Vehicle LOX Storage and Delivery System Schematic



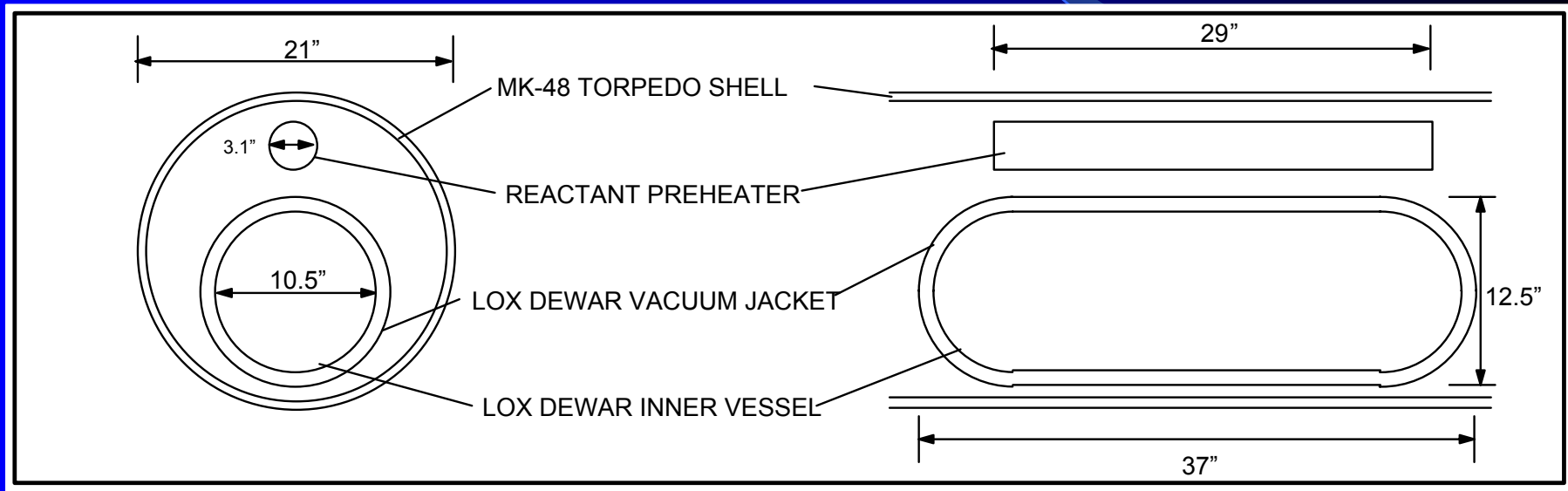


Sierra Lobo Cryo-Tracker™ Temperature and Liquid Level Sensing Probe Inside Cryogenic Tank





Unmanned Underwater Vehicle 50 kg Liquid Oxygen Storage and Delivery System Layout





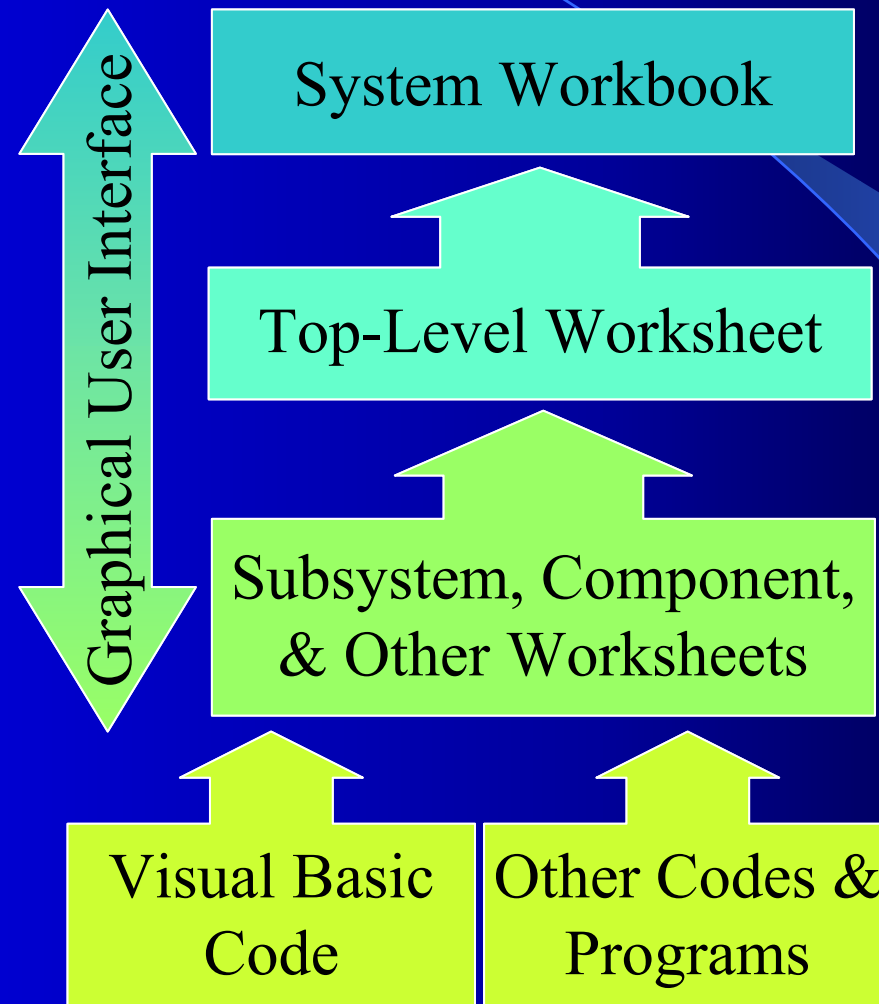
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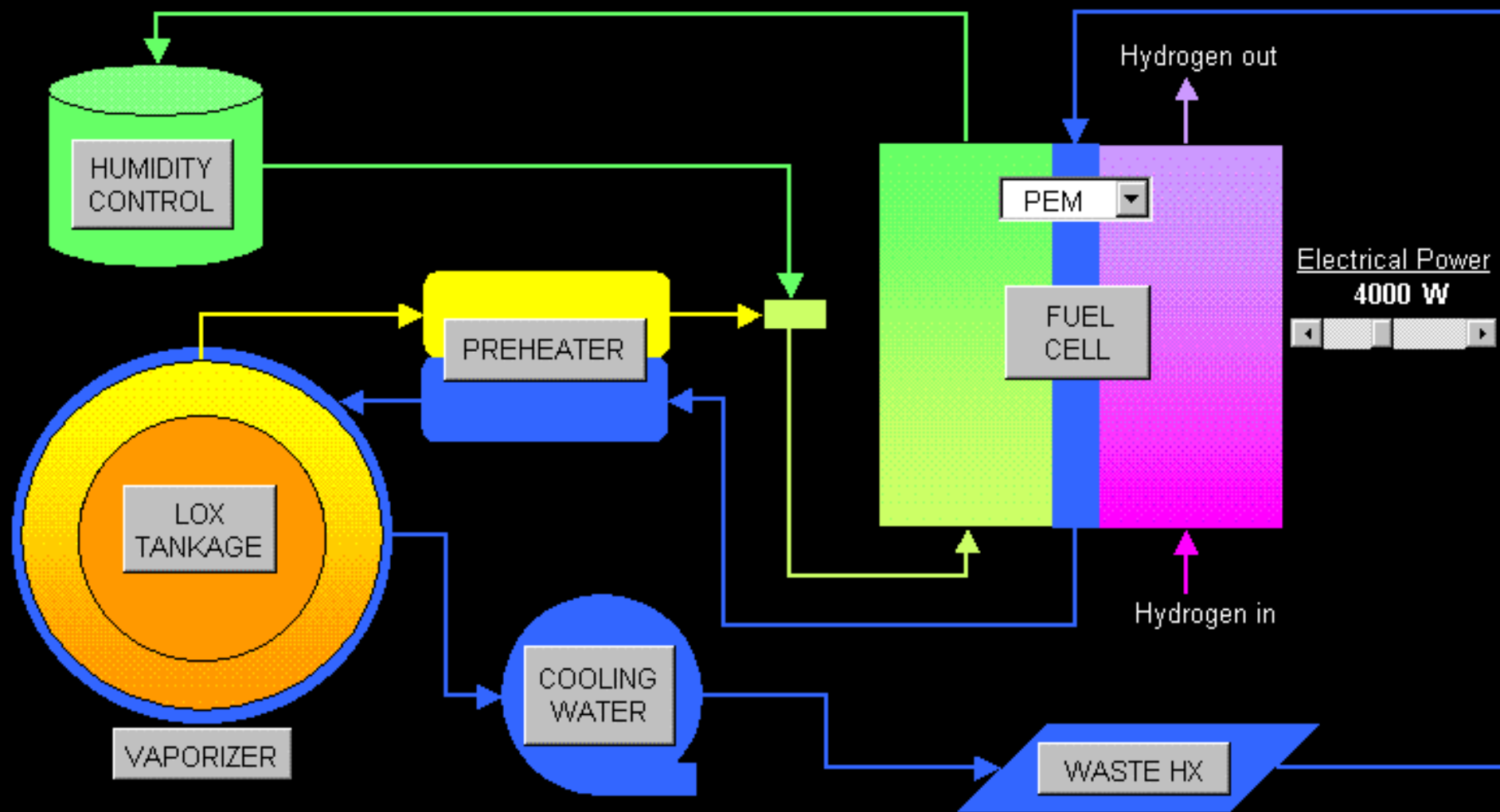
Fuel Cell and Cryogenic System Integrated Design Tool Methodology





DESIGN PROGRAM/MODELING

Main System Design Screen





DESIGN PROGRAM/MODELING

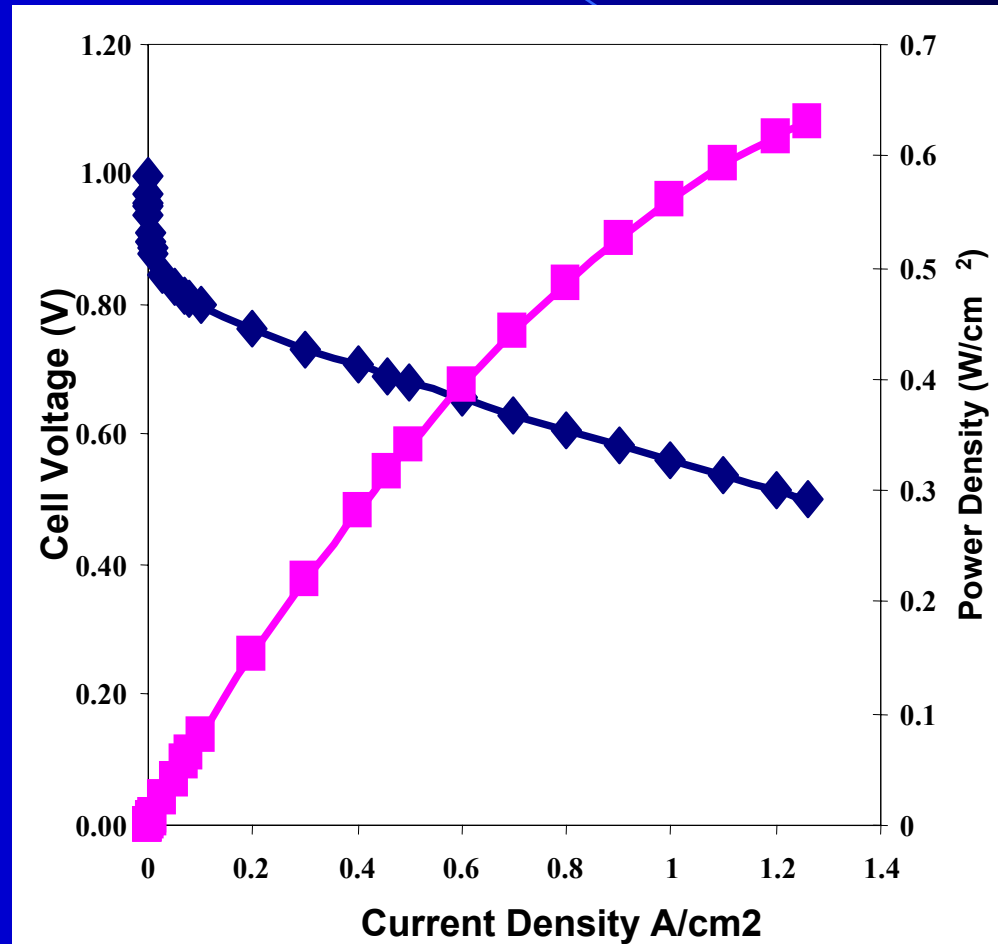
Lox Tankage Screen

Units	Sink temperature:	% of total area:	Foam:	Tank section	MLI layers:	Misc. factors:
☐ English	Area #1 300.0 K	41.2 %	0.10 m	outer diam	50	MLI factor: 50 %
☒ SI (metric)	Area #2 300.0 K	58.8 %	0.10 m	ends	50	Cond factor: 5 %
	Area #3 300.0 K	0 %	1.00 m	none	0	Mass factor: 10 %

Oxygen Fluid mass: 50.0 kg Fluid temp: 90.0 K Tank press: 101.0 kPa Ullage: 5 % Stainless Steel MEOP: 300.0 kPa Factor of Safety: 1.50 Stiffening rings: 10 thickness: 0.25 cm crossect area: 0.0122 cm ² length btwn: 0.039 m	 ☒ Cylindrical inside diameter: 0.44 m	CALCULATED TANK PARAMETERS Fluid density: 1142.107 kg/m ³ Internal volume: 0.05 m ³ Wall thickness: 0.0127 cm Dry mass: 0.66 kg Misc mass: 0.07 kg Heat leak: 0.64 W Conduction: 0.03 W Max outer diam: 0.60 m Max outer length: 0.84 m Min inner diam: N/A m
	 ☐ Spherical	
	 ☐ Annular	



PEM Fuel Cell Polarization Curve Model





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Unmanned Underwater Vehicle Hazard Matrix

Hazard Group*	Subsystem**	Oxygen System											Water System									
		Interface to Host	Storage Dewar	Cryo-Tracker	Heat Exchangers	Water Separator	Two-Phase Pump	Instrum. & Controls	Valves	Pipes	Electrical	Heater	Structural	Pump	Heat Exchangers	Heater	Instrum. & Controls	Valves	Pipes	Electrical	Ambient Radiator	Structural
Collision		-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	+
Mechanical Damage		-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	+
Contamination		+	+	+	+	+	-	+	+	-	-	-	-	-	+	-	-	-	-	-	-	-
Corrosion		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Electrical Shock		+	-	-	-	-	-	+	-	-	+	-	-	-	-	-	+	-	-	+	-	-
Explosion		-	+	-	+	+	-	-	+	+	-	-	-	-	+	-	-	+	+	-	-	-
Fire		+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	-	-	-	+	-	-
Loss of Habitable Atmosphere		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pathological		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Psychological		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Radiation		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Temperature Extremes		+	+	-	+	-	+	-	+	+	-	+	+	+	+	+	-	-	-	-	+	-

* Hazards groups defined by Reference 16.

** A subsystem failure or malfunction may cause damage in the hazard group(s) indicated



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Oxygen Storage Systems Comparisons (50 kg of Oxygen)

		Chemical	HP GOX	NBP LOX	TP LOX
Tank Material	Units		CC	Aluminum	Aluminum
Temperature	K (F)		300 (80)	90 (-297)	54 (-362)
Pressure	KPa (psia)		34473 (5000)	101.3 (15)	101.3 (15)
Fluid Density	kg/m ³ (lbm/ft ³)		435 (27)	1142 (71.3)	1306 (81.5)
Mass	kg (lbm)		11.6 (25.6)	4.1 (9.1)	3.4 (7.6)
Maximum Length	m (ft)		2.2 (7.07)	0.497 (3.08)	0.475 (2.76)
Oxidizer Mass Ratio		0.60 max	0.81	0.92	0.94

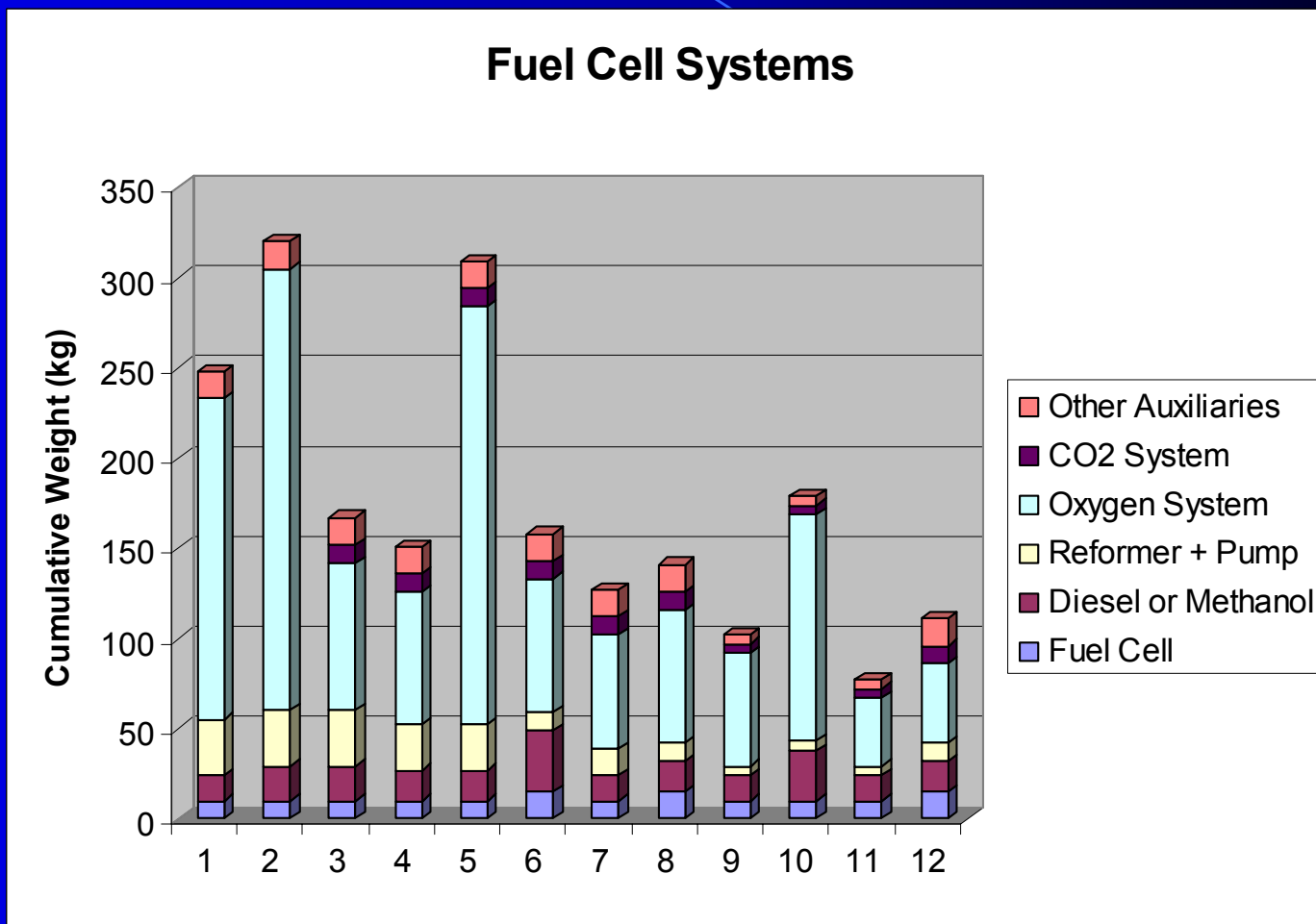


Specific Energies of Different Fuel Cell Types

System No.	Fuel Cell Type	Oxidizer	Specific Energy (Whr/kg)
1	PEM w/ Logistic	Chemical O2	367
2	PEM w/ Logistic	Chemical O2	284
3	PEM w/ Logistic	LOX	544
4	PEM w/ Syn-Diesel	LOX	602
5	PEM w/ Syn-Diesel	60% H2O2	294
6	PEM DMFC	LOX	575
7	SOFC w/ Logistics	LOX	713
8	SOFC DECO#1 (Near-Term)	LOX	643
9	SOFC DECO#2 (Long-Term)	LOX	887
10	SOFC DECO#3 (2x Energy)	LOX	1013
11	SOFC DECO#2 (AIP-Air Option (50:50))	LOX	1172
12	SOFC DECO#1 AIP-Air Option (50:50)	LOX	816



UUV Propulsion System Weights (100kWh @ 4 kW Fuel Cell)





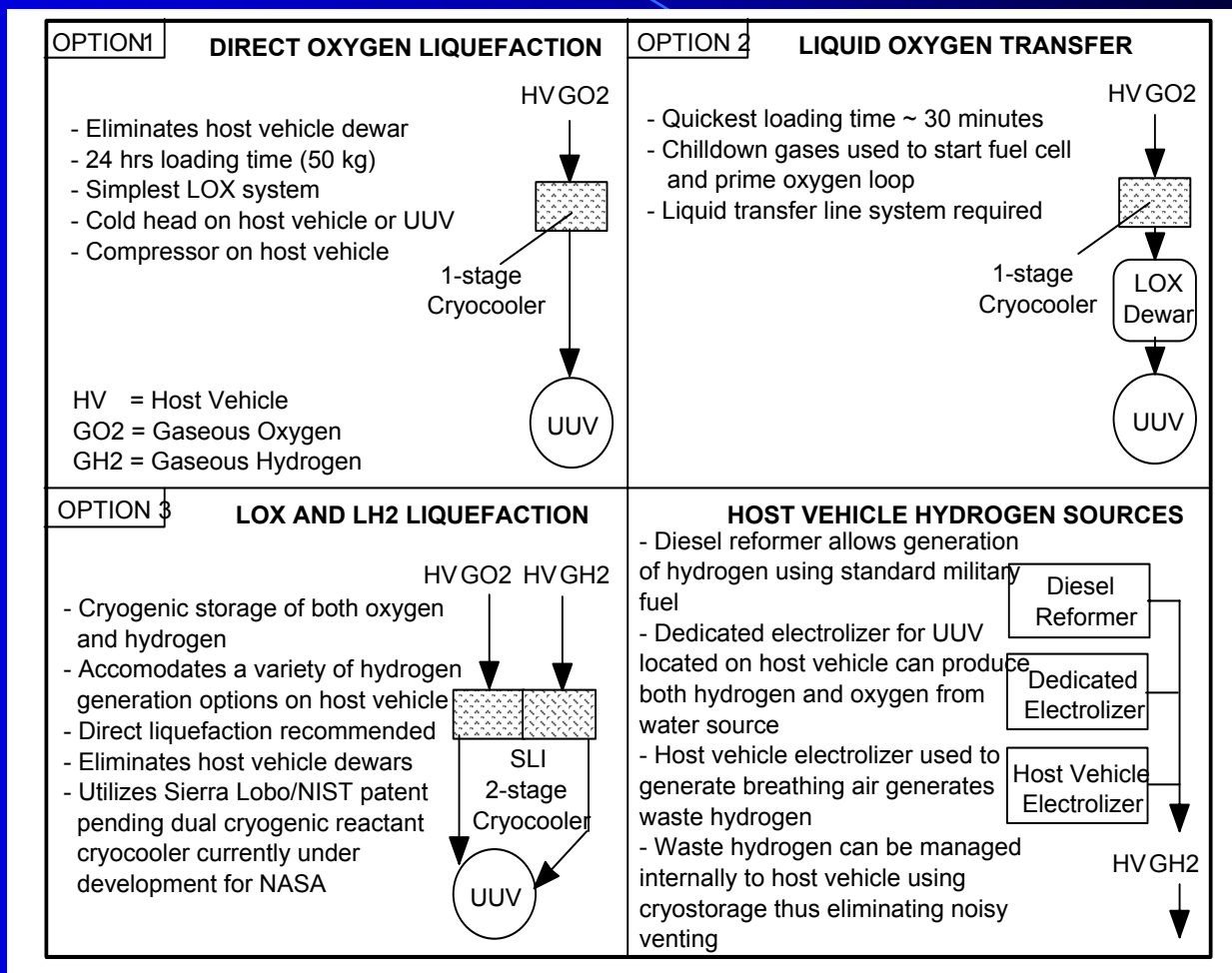
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Host Vehicle Cryogenic UUV Systems Support Options including Oxygen and Hydrogen

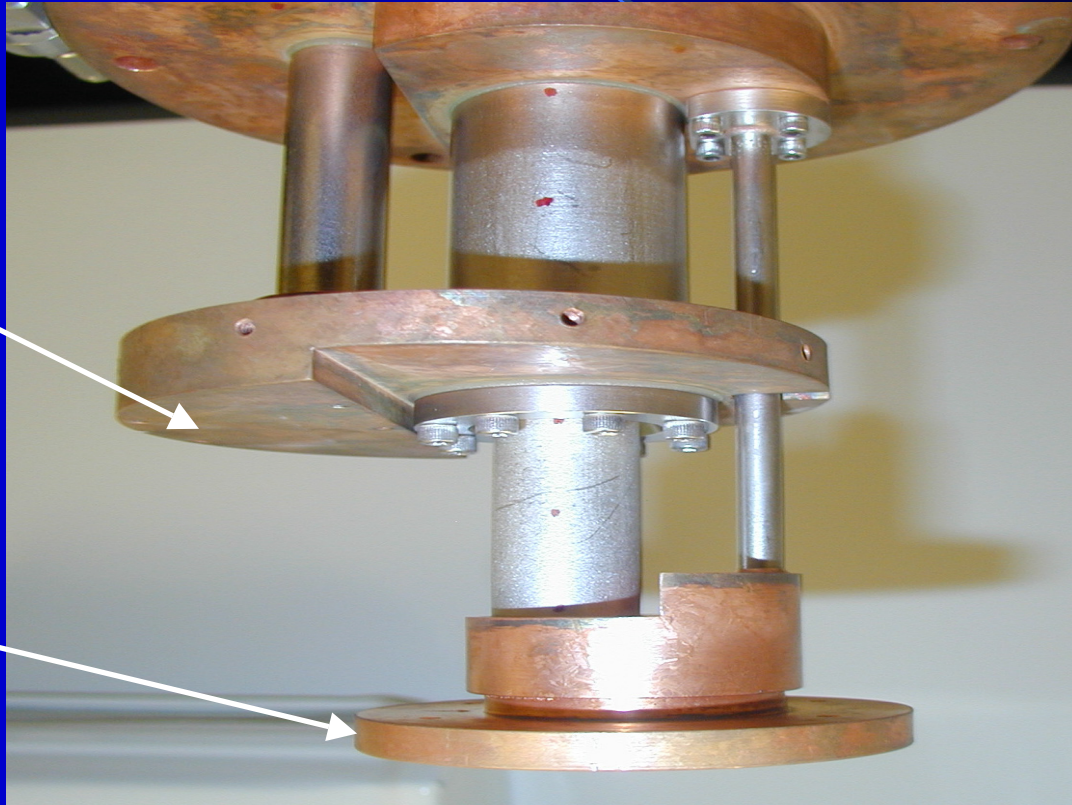




Sierra Lobo Two-Stage Pulse Tube Cryocooler

Stage 1
Oxygen Liquefaction

Stage 2
Hydrogen Liquefaction





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SUMMARY

- **SUCCESSFUL INTEGRATION OF CRYOGENIC SYSTEMS AND FUEL CELL SYSTEMS**
- **INTEGRATED SYSTEM DESIGN TOOL DEVELOPED**
- **PROVEN FEASIBILITY OF SAFE LOX SYSTEM FOR UUV**
- **ADVANCED MASS GAUGING AND CRYOCOOLER TECHNOLOGIES ENABLE “STORABLE” CRYOGENS**



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