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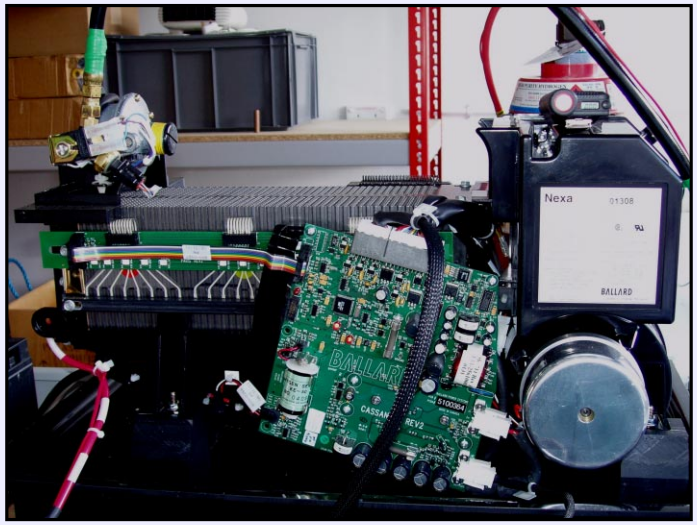
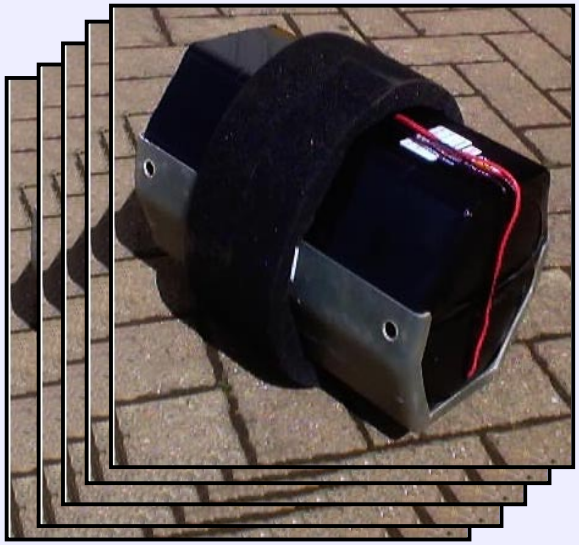
Cost vs. performance for fuel cells and batteries within AUVs





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This work was undertaken within the Battlespace Access UUV project.

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Motivation

- 2004 UUVS presentation asked the question: "Energy and power for AUVs: batteries or fuel cells?"
- Answered for technical performance: "Significant benefits in specific energy over secondary lithium batteries"
- Cost was not considered; so this paper …
  - Reviews cost of energy from primary batteries
  - Proposes costing method for energy from secondary batteries and derives typical cost
  - Uses similar method to cost energy from a marinised PEM fuel cell
- Poses some questions if using PEM fuel cells in an AUV

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Cost & performance of some primary batteries

Chemistry	Cost per cell in quantity (£)	Energy per cell (Wh)	Specific energy ($Wh.kg^{-1}$)	Cell cost per kWh (£)	Cost per kWh inc. assembly & disposal. (£)
Mn Alkaline	0.50	8 - 18	58 - 127	28 - 62	56 –90
Li MnO_2	8.00	31.5	270	254	310
Li SO_2	12.00	48	270	250	306
Li $SOCl_2$	9.50	33	470	288	344
Li CF_x	300.00	105	709	2857	2913

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Assumptions for secondary batteries

- Average AUV power demand will be 2 kW.
- AUV missions will last 100 hours or less.
- AUV will be in operational use 120 days of the year.
  (i.e. <50 charge-discharge cycles a year, should ensure 10-year life; battery will deliver 57,600 kWh (max) through life.
- Annual maintenance and safety-related costs are estimated to be 25% of the cost of the capital items.
- End of life disposal cost will be 5% of the capital cost.

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Cost & performance of Li-Po secondary batteries

Component	Capital cost	Amortised cost per kWh	Cost per year
200 kWh Li polymer battery at £913 per kWh	£182,600	£3.18	£18,260
Charging system (per four vehicles). Complete system at £200k split four ways.	£50,000	£0.87	£5,000
Cost of charging at £0.10 per kWh	-	£0.10	£576
Maintenance and safety charges at 25%.	-	£1.04	£5,990
End of life disposal at 5%	-	£0.26	£1,498
TOTAL	**£232,600**	**£5.45**	**£31,324**

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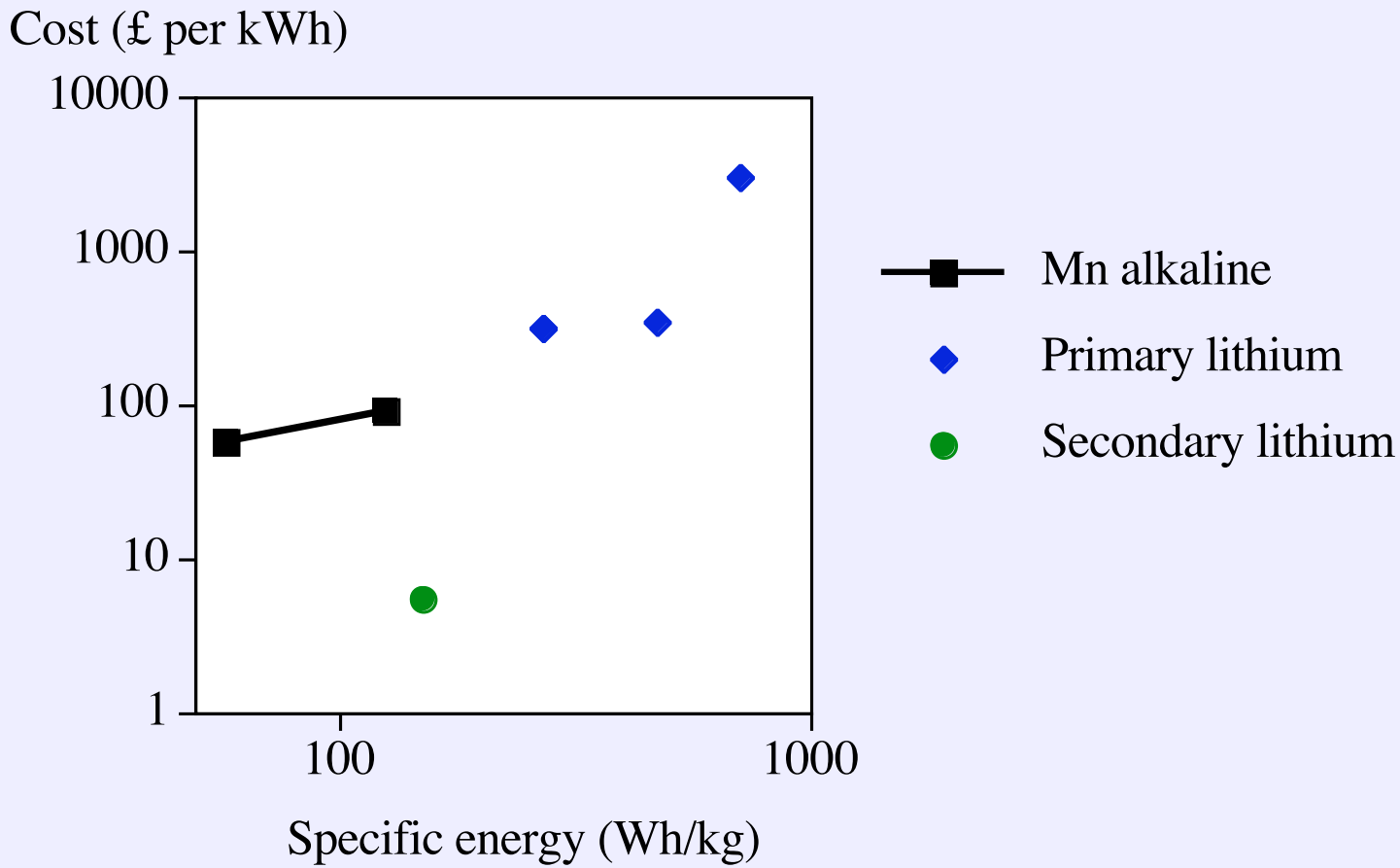
Cost vs. performance of batteries



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Cost factors for Fuel Cell

- Fuel cell stack with its support systems
- Marinising the fuel cell
- Reactant storage
- Marinising the reactant stores
- Cost of reactants
- Depreciation over useful life – assume 2 years
- Maintenance costs – assume 25% per annum
- End-of-life disposal – assume 5% of capital cost

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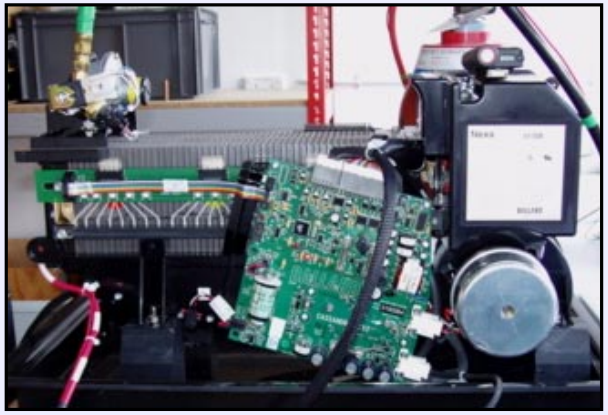
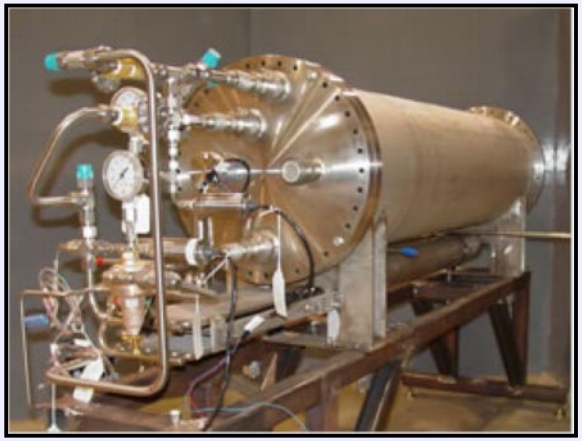
Some possible fuel cell system components



NOCS

COTS Nexa 1.2 kW PEM fuel cell system from Ballard. Cost ~ €5900



Sierra Lobo Inc.

Cryogenic oxygen system from Sierra Lobo Inc. Stores 50 kg of LOX in 21" UUV form factor.

Composite hydrogen storage cylinders

e.g. DyneCell 450
Stores 8.64 kg H_2
Weighs 170 kg

www.dynetek.com

Genesis Fueltech reformer Methanol/Water premix. Net efficiency: 80% Weighs: 21 kg

Genesis Fueltech

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Cost of reactants

Reactant	Cost per kWh (£)	Liquid O_2	Gasseous O_2	From H_2O_2
Cost per kWh (£)		£0.24	£0.18	£1.15
Liquid H_2	£0.36	£0.60	£0.54	£1.51
Compressed H_2	£0.45	£0.69	£0.63	£1.60
Reformed from methanol	£0.09	£0.33	£0.27	£1.24

Note: these are cost in bulk. Smaller quantities are more expensive. For example, a size 'K' Hydrogen cylinder, with 7200 litres of gas, realistically about 7.5 kWh, costs £5.74 for the gas, and £9.20 to deliver. A *gas* cost of £0.76 per kWh. (BOC July 2005)

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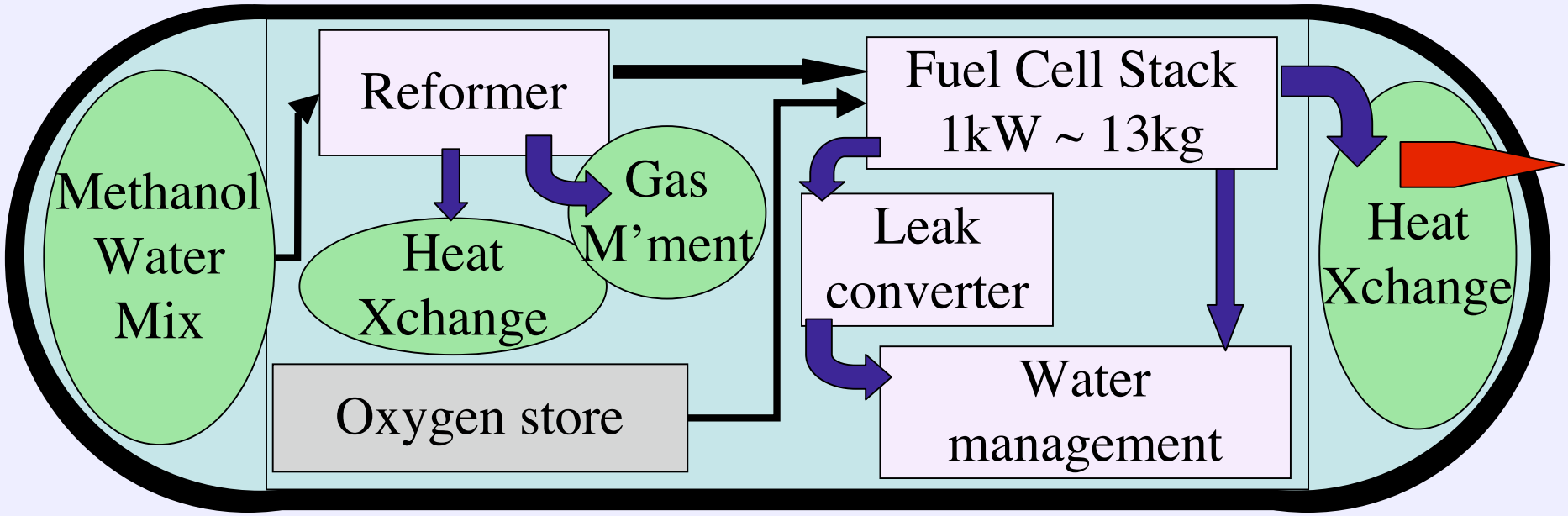
The Big Issue: a marinised PEM H_2/O_2 fuel cell

One possible configuration …



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Cost of fuel cell energy

Component	Capital cost	Amortised cost per kWh	Cost per year
Marinised PEM Fuel cell system (2kW, 2yr life, 5760hr mission time)	£85,000	£7.40	£42,500
Reactant store e.g. compressed H_2 and LOX	£198,000	£17.20	£99,000
Maintenance cost at 25%	-	£6.15	£35,375
Consumables	-	£0.27–£1.60	£1,555–9,216
End of life disposal at 5%	-	£1.62	£7,075
TOTAL	**£283,000**	**£32.91 - £34.24**	**£189,560 - £197,220**

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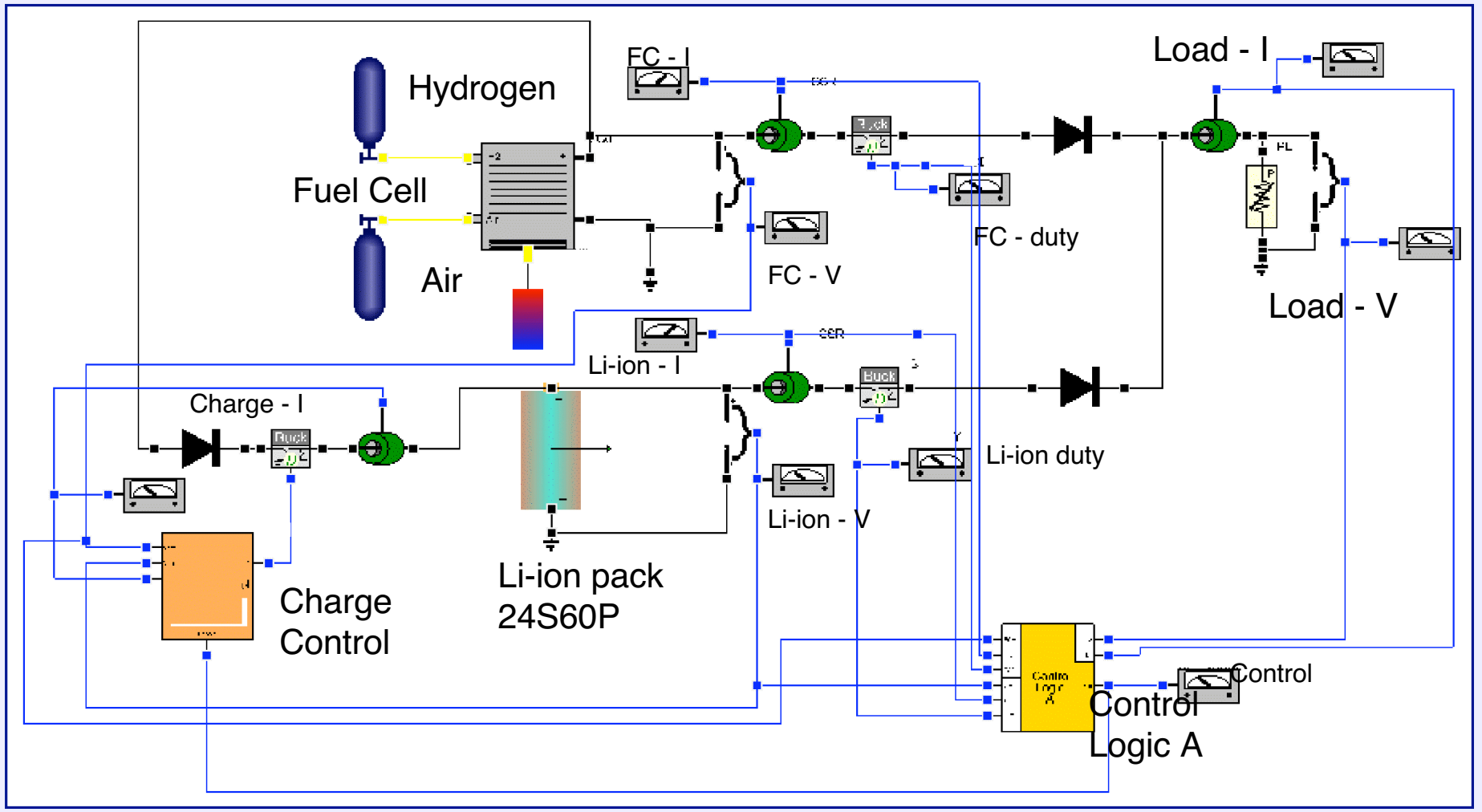
VTB schematic for hybrid fuel cell/Li-ion hybrid



Courtesy David Reece, AEA Technology, for BAUUV

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Cost of fuel cell-battery hybrid energy

Component	Capital cost	Amortised cost per kWh	Cost per year
Li polymer battery (121kWh) 10 year life	£110,500	£1.24	£11,050
Share of charging system (per 4 vehicles) (shore/ship use)	£50,000	£0.56	£5,000
Marinised PEM Fuel cell system (10kW, 2yr life, 5760hr mission time)	£125,000	£7.02	£62,500
Reactant store e.g. compressed H_2 and LOX	£198,000	£11.13	£99,000
Consumables (max)	-	£1.60	£14,250
Maintenance cost at 25%	-	£5.40	£48,050
End of life disposal at 5%	-	£1.35	£12,010
TOTAL	**Initial: £483,500**	**£28.30**	**£251,860**

Based on hybrid lithium polymer and fuel cell system designed for 7-day operation with occasional peak power of 32 kW (8897 kWh per year).

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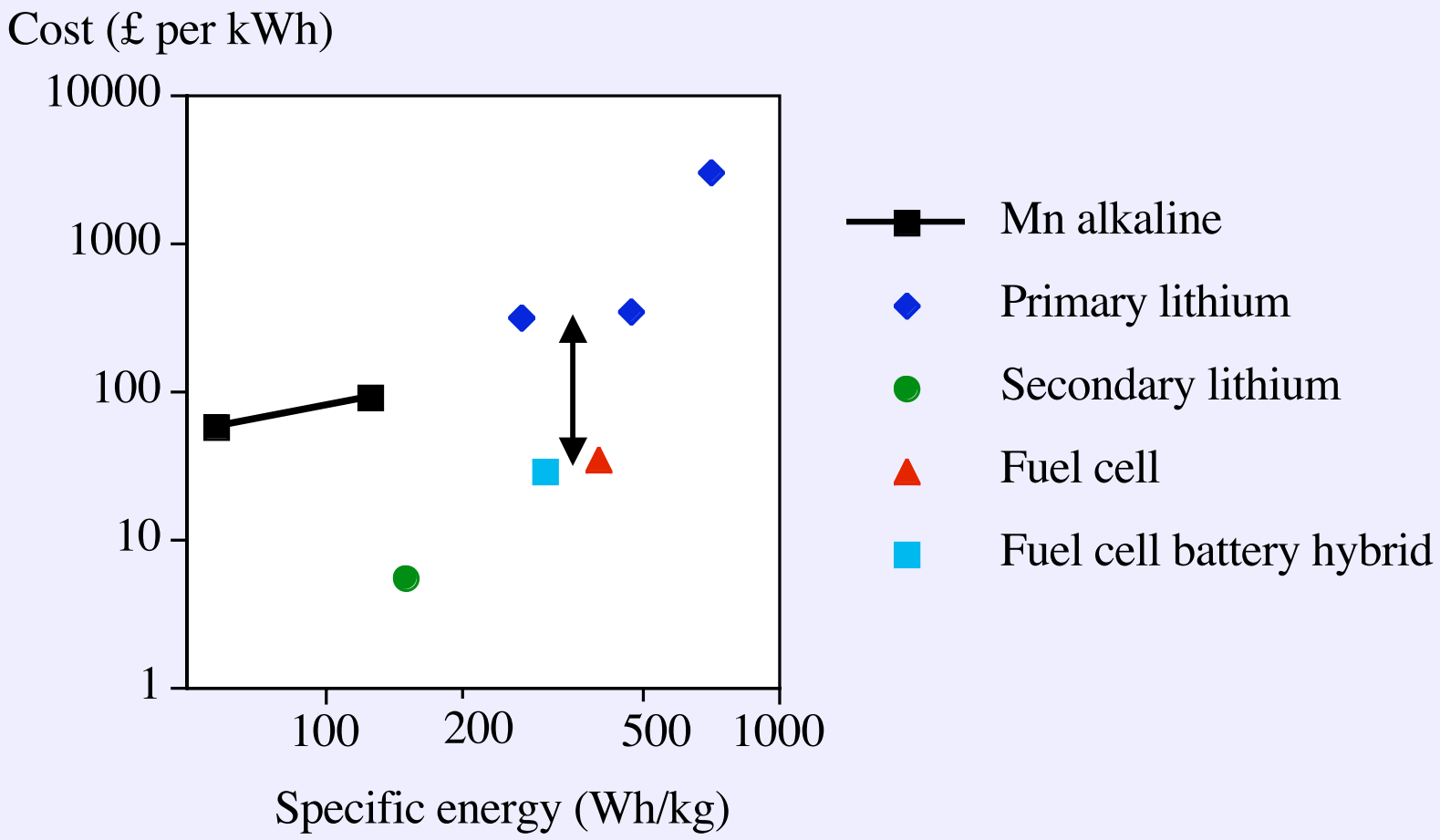
Cost vs. performance of fuel cell and batteries



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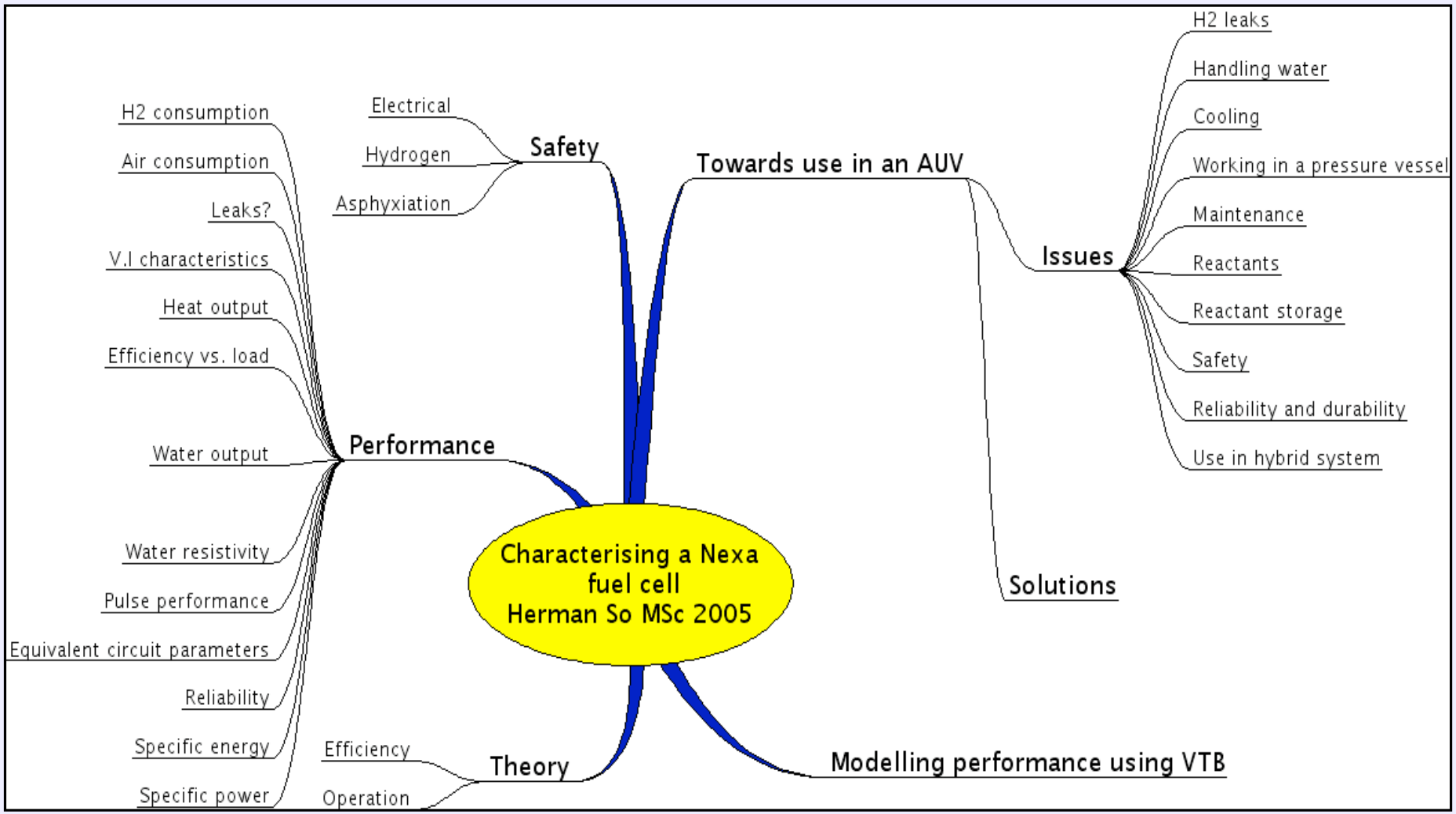
Characterising a Nexa 1.2 kW fuel cell system



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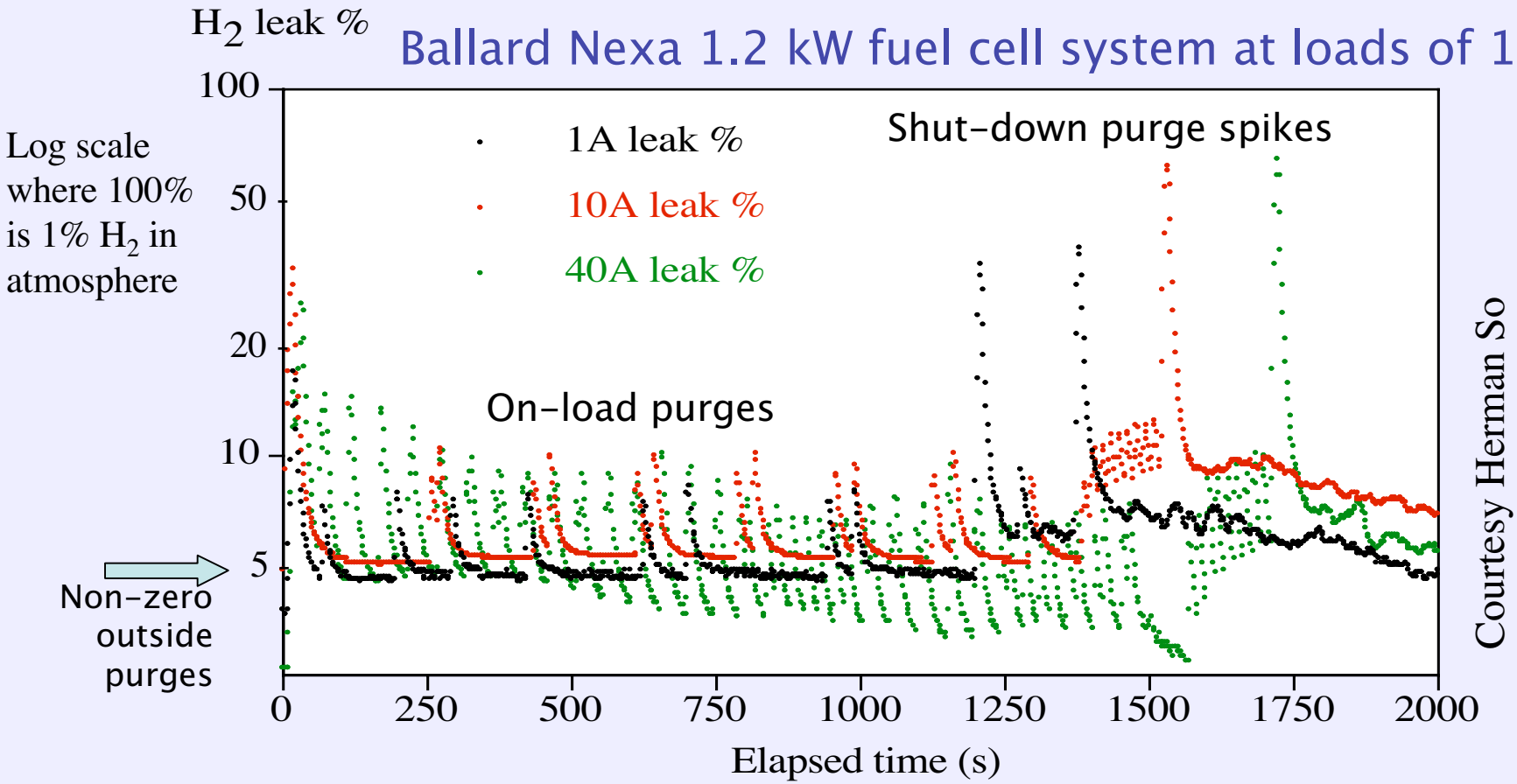
Hydrogen purging: under load and at shut-down

Ballard Nexa 1.2 kW fuel cell system at loads of 1-40A



Escape of hydrogen into the cooling air flow is a regular by-product of purging - the process of ridding the cells of produced water.

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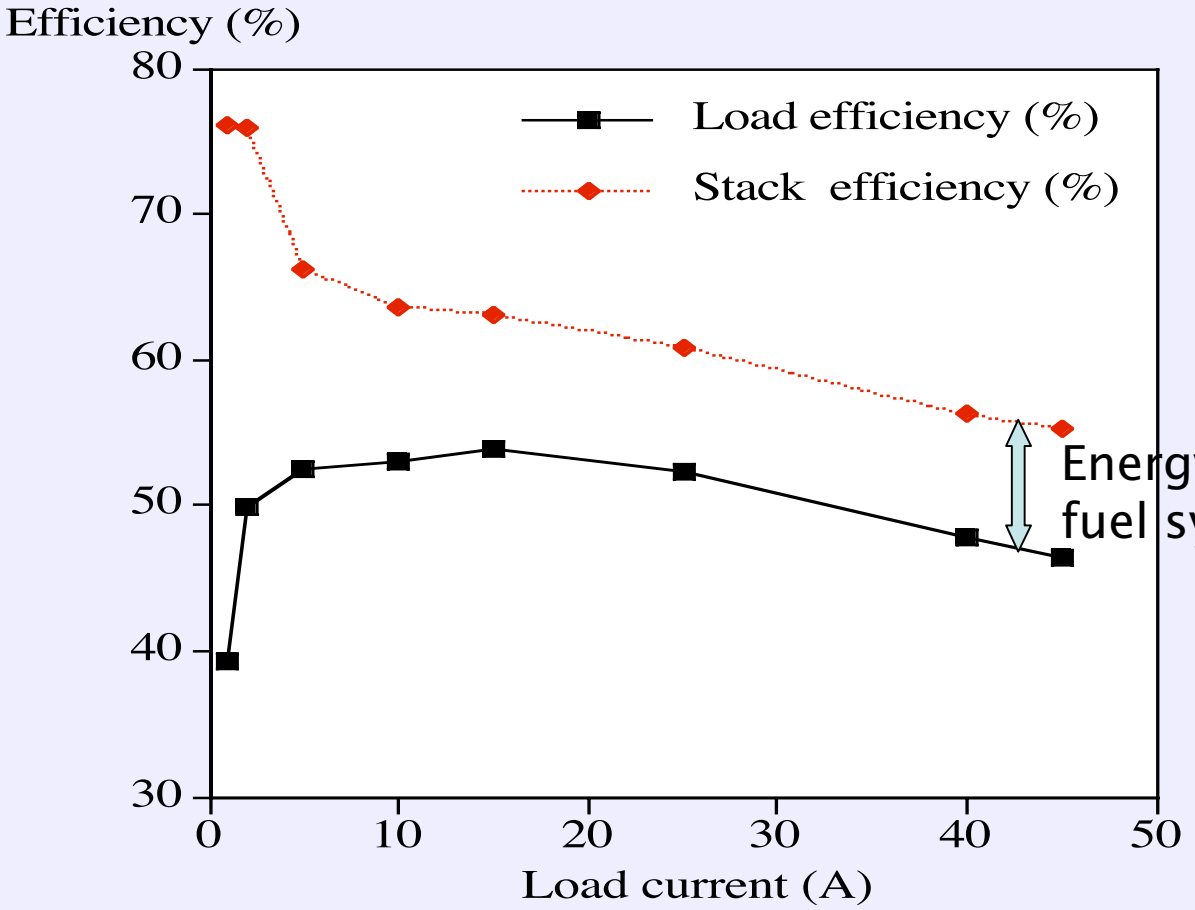
More realistic fuel cell modelling needed



Load and stack efficiency of a Ballard Nexa 1.2 kW fuel cell system, courtesy Herman So

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Conclusions

- Primary battery energy sources exist today, off-the-shelf, with higher specific energy than what PEM fuel cells may deliver within an UUV over the next 5 years.
  However, at an energy cost of over £2000 per kWh.
- Secondary lithium batteries provide energy at about £5.45 per kWh, excellent life expectancy of ~10 years, high specific power, and cost of cells may continue to fall.
- PEM fuel cells have the potential for matching, or even improving on, the system specific energy of primary lithium thionyl chloride cells, based on hydrogen storage at 6% by mass and cryogenic oxygen storage. At a cost of ~£33 per kWh.
- Key drivers are costs of marinisation and reactant storage.
- For hybrid fuel cell- battery systems, costs dominated by fuel cell and reactant storage.
- Reactant cost is a small fraction of the overall cost. Tradeoffs between more expensive, but easily stored, reactants and the cost of the hardware are worth investigating.