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Analysis of Ultracapacitor-VRLA Energy Storage Systems for Mild Hybrids

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Background

- FreedomCAR's Goals for mild hybrids are aggressive for batteries. Could ultracapacitors play a role?

FreedomCAR 42 V Energy Storage System End-of-Life Performance Goals (August 2002)

42 Volt Targets Rev. August 2002	Start-Stop		M-HEV		P-HEV	
Discharge Pulse Power (kW)	6	2 s	13	2 sec	18	10 sec
Regenerative Pulse Power (kW)	N/A		8	2 sec	18	2 s
Engine-Off Accessory Load (kW)	3	5 min	3	5 min	3	5 min
Available Energy (Wh @3 kW)	250		300		700	
Recharge Rate (kW)	2.4 kW		2.6 kW		4.5 kW	
Energy Efficiency on Load Profile (%)	90		90		90	
Cycle Life, Miles/Profiles (Engine Starts)	150k (450k)		150k (450k)		150k (450k)	
Cycle Life and Efficiency Load Profile	Zero Pwr Asst (ZPA)		Partial Pwr Asst (PPA)		Full Pwr Asst (FPA)	
Cold Cranking Power @ -30°C (kW)	8	21 V Min.	8	21 V Min.	8	21 V Min.
Calendar Life (Yrs)	15		15		15	
Maximum System Weight (kg)	10		25		35	
Maximum System Volume (Liters)	9		20		28	
Selling Price ($/system @ 100k/yr)	150		260		360	
Maximum Open Circuit Voltage (Vdc) after 1 Sec.	48		48		48	
Minimum Operating Voltage (Vdc)	27		27		27	
Self Discharge (Wh/day)	<20		<20		<20	
Heat Rejection Coefficient (W/°C)	N/A		N/A		>30	
Maximum Cell-to-Cell Temperature Difference (°C)	N/A		N/A		<4	
Operating Temperature Range (°C)	-30 to +52		-30 to +52		-30 to +52	
Survival Temperature Range (°C)	-46 to +66		-46 to +66		-46 to +66	

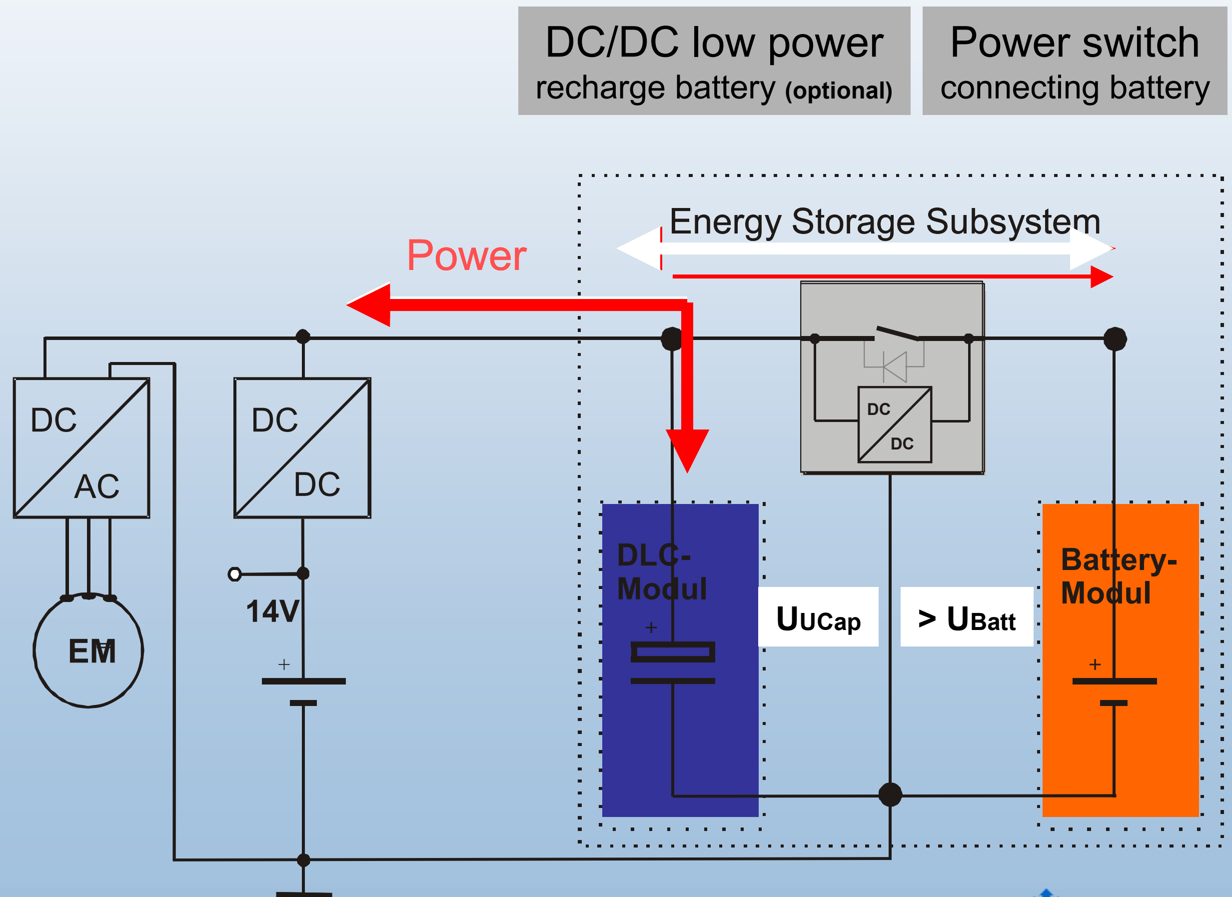
Background (cont.)

- FreedomCAR's gaols for ultracapacitors are also aggressive. Could VRLAs play a role?

System Attributes	12V Start-Stop (TSS)		42V Start-Stop (FSS)		42V Transient Power Assist (TPA)	
Discharge Pulse	4.2 kW	2s	6 kW	2s	13 kW	2s
Regenerative Pulse	N/A		N/A		8 kW	2s
Cold Cranking Pulse @ -30°C	4.2 kW	7 V Min.	8 kW	21 V Min.	8 kW	21 V Min.
Available Energy (CP @1kW)	15 Wh		30 Wh		60 Wh	
Recharge Rate (kW)	0.4 kW		2.4 kW		2.6 kW	
Cycle Life / Equiv. Road Miles	750k / 150,000 miles		750k / 150,000 miles		750k / 150,000 miles	
Cycle Life and Efficiency Load Profile	UC10		UC10		UC10	
Calendar Life (Yrs)	15		15		15	
Energy Efficiency on UC10 Load Profile (%)	95		95%		95%	
Self Discharge (72hr from Max. V)	<4%		<4%		<4%	
Maximum Operating Voltage (Vdc)	17		48		48	
Minimum Operating Voltage (Vdc)	9		27		27	
Operating Temperature Range (°C)	-30 to +52		-30 to +52		-30 to +52	
Survival Temperature Range (°C)	-46 to +66		-46 to +66		-46 to +66	
Maximum System Weight (kg)	5		10		20	
Maximum System Volume (Liters)	4		8		16	
Selling Price ($/system @ 100k/yr)	40		80		130	

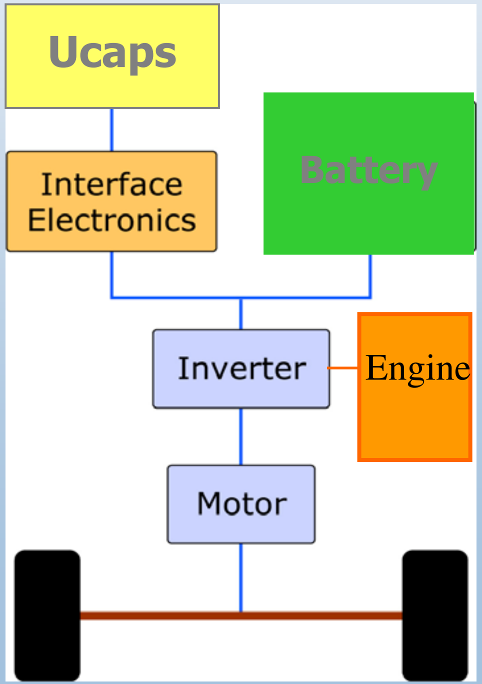
Background (concl.)

- In AABC-2004, Continental Temic presented a concept on combining lead acid batteries and ultracapacitors through DC/DC converters to meet the targets of mild hybrids. How does this concept compares with battery alone solutions in meeting targets?



Motivation for this Study

- There is some believe that all the performance, life, and cost goals set for energy storage system in mild 42V hybrids could not be met with advanced batteries.
- What is the potential of dual energy storage systems such as combining valve regulated lead acid (VRLA) and ultracapacitors in meeting the targets?



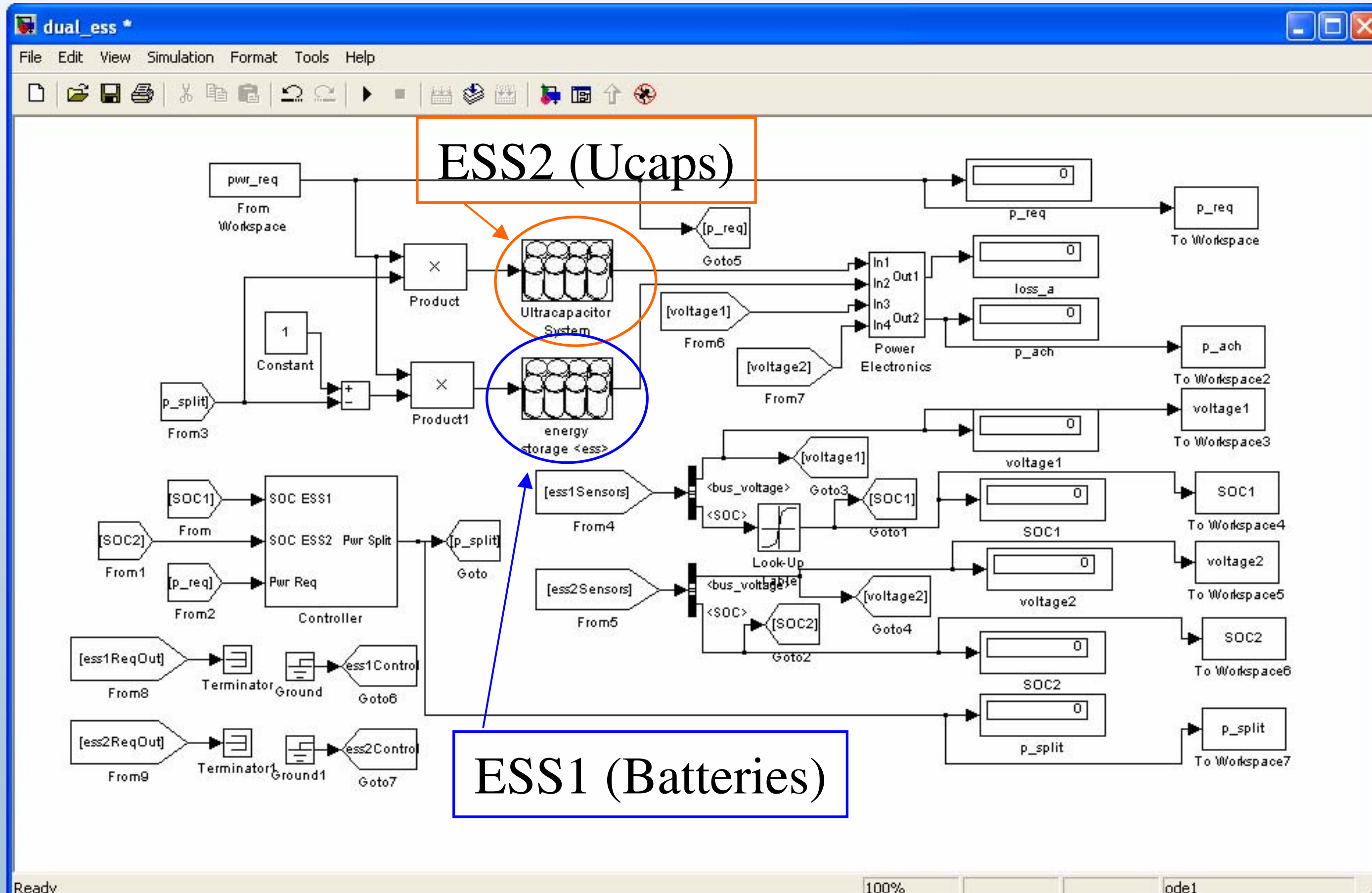
42 Volt Targets Rev. August 2002	M-HEV	
Discharge Pulse Power (kW)	13	2 sec
Regenerative Pulse Power (kW)	8	2 sec
Engine-Off Accessory Load (kW)	3	5 min
Available Energy (Wh @3 kW)	300	
Recharge Rate (kW)	2.6 kW	
Energy Efficiency on Load Profile (%)	90	
Cycle Life, Miles/Profiles (Engine Starts)	150k (450k)	
Cycle Life and Efficiency Load Profile	Partial Pwr Asst (PPA)	
Cold Cranking Power @ -30°C (kW)	8	21 V Min.
Calendar Life (Yrs)	15	
Maximum System Weight (kg)	25	
Maximum System Volume (Liters)	20	
Selling Price ($/system @ 100k/yr)	260	
Maximum Open Circuit Voltage (Vdc) after 1 Sec.	48	
Minimum Operating Voltage (Vdc)	27	
Self Discharge (Wh/day)	<20	
Heat Rejection Coefficient (W/°C)	N/A	
Maximum Cell-to-Cell Temperature Difference (°C)	N/A	
Operating Temperature Range (°C)	-30 to +52	
Survival Temperature Range (°C)	-46 to +66	

Objectives

- Develop strategies in analyzing dual volt energy storage systems
  - Dynamic analysis – equivalent circuit modeling (in Matlab)
  - Vehicle simulations (ADVISOR™)
- Analyze a combined VRLA and Ucap system in meeting 42V mild hybrid targets
- Compare VRLA+Ucap with advanced batteries

Dynamic Modeling Approach

- Uses existing equivalent-circuit energy storage models from ADVISOR™ library to model complete system
- Can be used in stand-alone mode or linked back to vehicle model



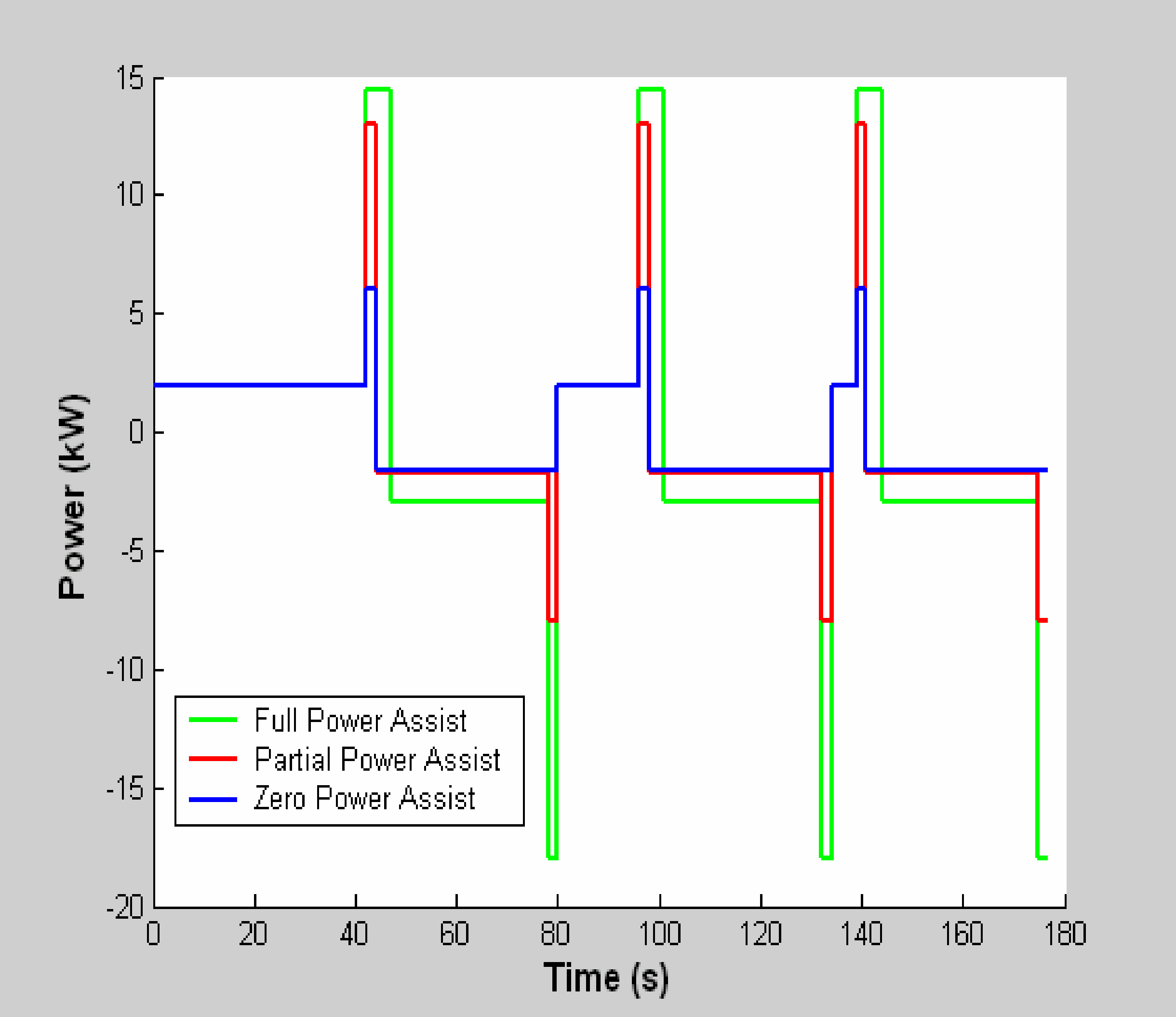
Key Assumption

Power electronics will not limit dynamic response and will provide requested boost and power transmission levels with some efficiency penalty

Selected 42V Power Profiles for Analysis

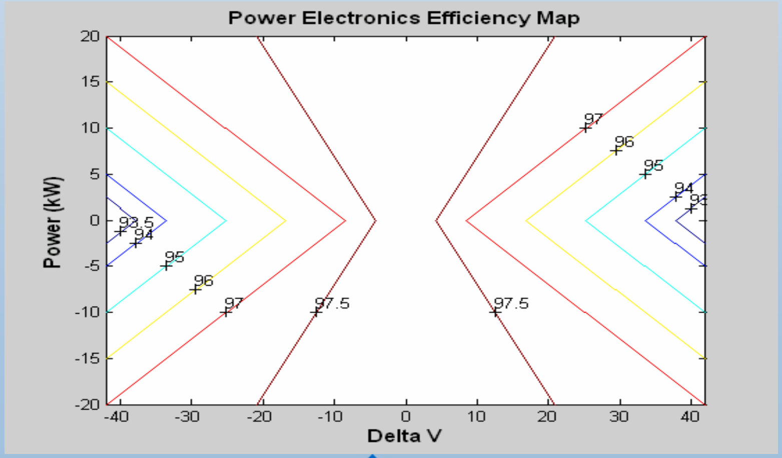
(FreedomCAR 42V Battery Test Manual, *DOE/ID-11070*, April 2003)

- Zero Power Assist includes no regen capture
- Full Power Assist includes 10s discharge for acceleration
- Drive cycle analysis of various profiles and vehicle testing experience indicates regen events are typically longer than 2s
  - More likely 4-5s



Input Parameters

- ESS Model inputs
  - VRLA: Hawker Genesis 25 Ah
    - SOC Limits: 0.6-0.9
    - Voltage Limits: 9.5V-16.5V
    - Mass: 11 kg/module
  - Ultracap: Maxwell 2500F
    - SOC Limits: 0.5-1.0
    - Voltage Limits: 1.25V-2.7V
    - Mass: 0.71 kg/module
- Power electronics inputs
  - Mass: 1 kg/kW
  - Efficiency: f(Power, V1/V2)
- Other ESS technologies
  - Li-ion: Saft 6Ah
    - SOC Limits: 0.6-0.9
    - Voltage Limits: 2.0V-4.1V
    - Mass: 0.37 kg/module
  - NiMH: Panasonic Prismatic 6Ah
    - SOC Limits: 0.6-0.9
    - Voltage Limits: 6V-9V
    - Mass: 1 kg/module



Power Split Strategies between VRLA & Ucap in Combined ES System

- Ucap protects battery from high power transients
- Peak power ratings for each system individually result in base power split set-point for both charge and discharge events
- Rate term forces greater portion of power request towards the Ucap during transients
- SOC term modifies request to maintain SOC of both storage devices
- Low power charge and discharge events (below 1 kW) are handled entirely by battery
- Rate term = 5 kW/s
  - Transient power requests above this value will be pushed toward the Ucap
  - Below this, value are proportionally split between the two sources

Example of Control Strategy for VRLA+Ucap

Always accept regen up to limits. Always bring ucap up to mid point first, then battery.	**Battery low**	**Battery mid**	**Battery high**
Ucap low	Bat:Don't discharge unless needed for power, wait for regen Ucap: Don't discharge unless needed for power, wait for regen	Bat: discharge to bring ucap up to mid point Ucap: don't discharge, take charge from battery	Bat: discharge to bring ucap up to mid point Ucap:take charge from bat
Ucap mid	Bat:do nothing Ucap: do nothing unless needed for power	Bat: do nothing unless needed for power or eff op of engine Ucap: do nothing unless needed for power or efficient operation of engine	Bat: provide power for propulsion Ucap do nothing unless needed to supplement bat power
Ucap high	Bat: take charge energy from ucap Ucap: discharge to bat	Bat: do nothing Ucap: provide power for propulsion	Bat: provide power for propulsion Ucap: use for power propulsion

Evaluating Response of ES System
(attributes considered)

- Total Mass (minimize)
  - Sum of module masses + power electronics mass
- Total Cost (minimize)
  - Sum of module costs + power electronics cost
- Total Regen (maximize)
  - Percentage of regen available that is captured
- Total Loss (minimize)
  - Combination of ESS and PE losses over the cycle
- Time in Red Zone (minimize)
  - Sum of time battery is within 5% of voltage limits, a condition that reduces life

- Other Responses
  - Cumulative Trace Misses
    - Integral of difference between requested and achieved power outputs
  - Peak Trace Misses
    - Greatest difference between requested and achieved power outputs
  - Average Voltage Ratio
  - Min/Max Battery Power

Case Study Summaries
Initial Results for Meeting 42V M-HEV Profile

Case	Description	ESS1_Num	ESS2_Num	Mass	Energy Loss	Regen	RedZone Time
		#	#	Kg	Wh	--	Sec
1	Baseline UC – matched voltage	20	3	77.2	100.6	0.986	38
2	Reduced UC	7	3	48.5	138.7	0.967	53
3	Lead acid only	0	3	33	153.3	0.839	171
4	UC Only	20	0	44.2	83.7	0.948	0
5	Optimum. PbA and UC	10.2	5	77.6	110.7	0.996	9
6	Optimum PbA, UC, and	6.4	5	69.2	110.9	0.991	1
7	Optimum UC only	72	0	159.1	73.7	1	0
8	Optimum PbA only	0	7	77	110	1	0
9	Li-ion only	0	30	11.3	50.3	0.995	103
10	NiMH only	0	16	16	68.6	0.994	94

Initial Results:
Case Study Summaries For 42V Hybrid

Case	Description	ESS1_Num	ESS2_Num	Mass	Loss	Regen	RedZone Time	ESS2 Min Pwr	ESS2 Max Pwr	Cum Trace Miss	Peak Trace Miss	DeltaSOC1	DeltaSOC2	Obj
		#	#	*kg*	*Wh*	--	*s*	*kW*	*kW*	*Wh*	*kW*	--	--	--
1	Baseline - matched voltages	20	3	77.2	100.6	0.98626	38	-8091.43	6370.43	6.17	3.35	-0.0357151	-0.0643018	2.94
2	Reduced UC	7	3	48.5	138.7	0.966742	53	-8220.42	7323.59	30.11	8.32	0.049704	-0.0900061	3.14
3	Lead acid only	0	3	33	153.3	0.838809	171	-8609.95	7306.19	89.58	7.65	0	-0.172421	5.93
4	UC only	20	0	44.2	83.7	0.947857	0.0	0	0	82.79	11.73	0.192294	0	3.94
5	Opt. PbA and UC	10.2	5	77.6	110.7	0.995727	9	-12956.4	8395.89	6	3.40	0.00807023	-0.0383088	1.96
6	Opt. PbA, UC, and fixed split ratio	6.4	5	69.2	110.9	0.989705	1	-9480.71	10037.9	20.2	3.27	0.206621	-0.0381189	1.78
7	Opt. UC only	72	0	159.1	73.7	1.00634	0	0	0	5.58	0.36	0.0229676	0	6.07
8	Opt. PbA only	0	7	77	110	1	0	-13157.9	13931.2	2.86E-13	7.28E-15	0	-0.0375241	0.85
9	Li-ion only	0	30	11.3	50.3	0.991295	103	-13157.9	13931.2	3.37	3.68	0	-0.0250984	0.86
10	**NiMH only**	**0**	**16**	**16**	**68.6**	**0.994244**	**94**	**-13157.9**	**13931.2**	**2.23**	**3.77**	**0**	**-0.098452**	**0.30**

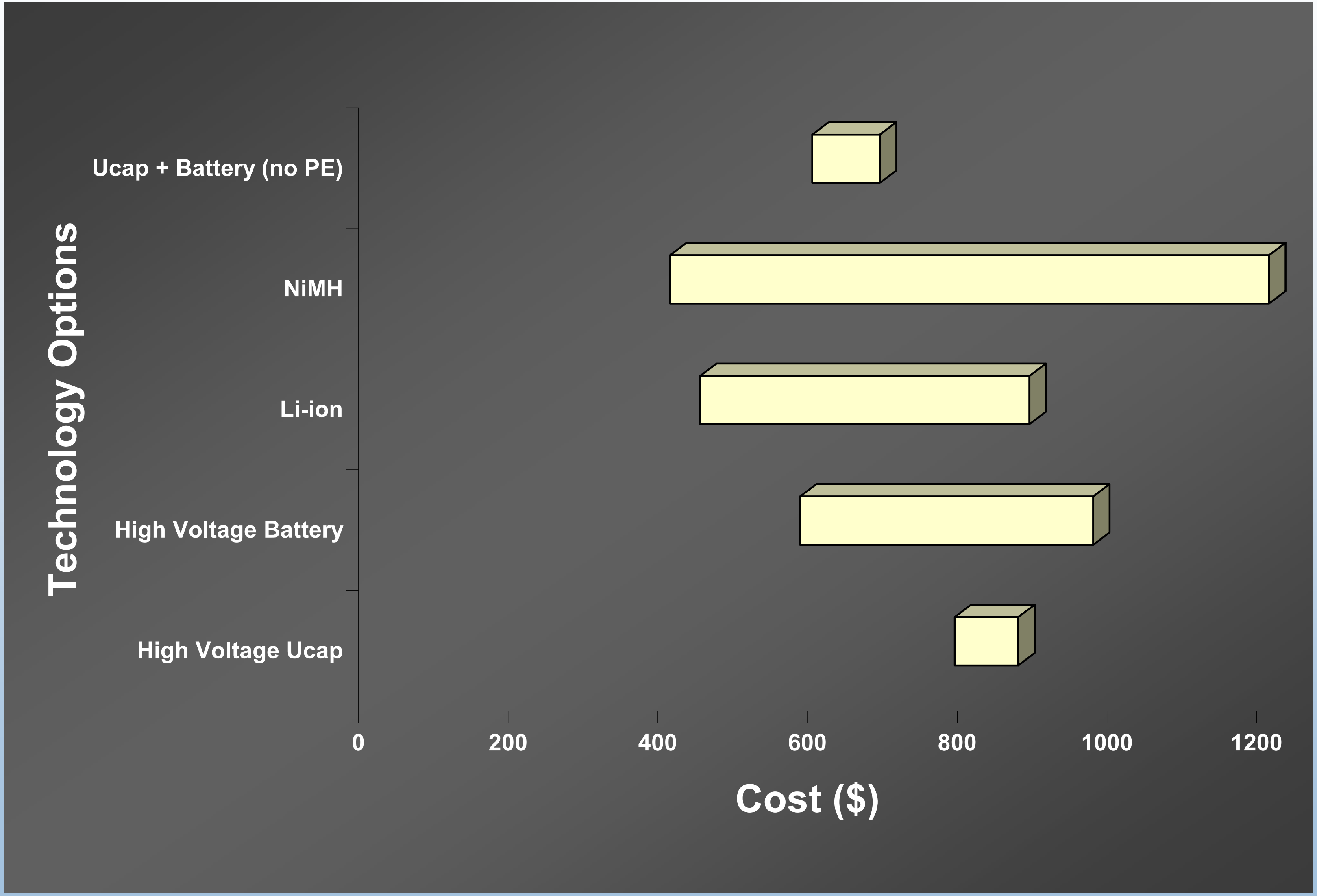
- Case 5 and 6 push Ucap-PbA design toward less Ucaps/ more battery to improve cost and reduce red time
- NiMH only case is not the worst or best in any one category but provides a good overall option
- Lightest most efficient system is Li-ion only

Comparing Dual ESS Options (Existing Technologies)

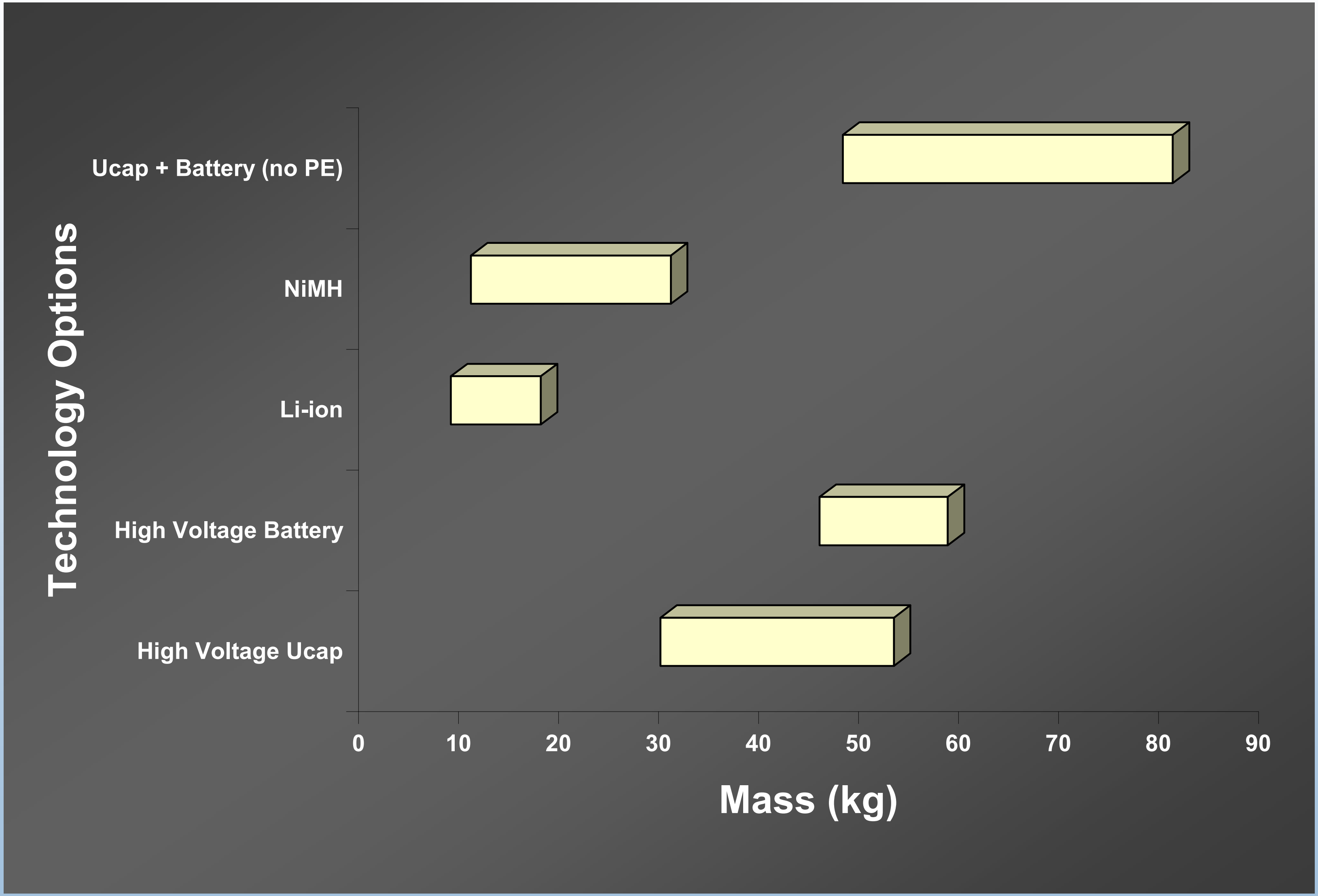
- High voltage Battery
  - Cost = $90+$250+PE_var+UC=$340+…
  - Mass = 33+3.75+PE_var+UC=36.75+…
  - Volume = 11.6+4.1+PE_var+UC=15.7+…
- High voltage UCap
  - Cost = $500+$250+PE_var+Bat=$750+…
    - Maybe $250+$250+PE_var+Bat = $500+…
  - Mass = 14.2+3.75+PE_var+Bat=18+…
  - Volume = 12.2+4.1+PE_var+Bat=16.3+…

- Other technologies
  - Li-ion
    - Cost = $440-$880
    - Mass = 8-17 kg
    - Volume = 7-13 L
  - NiMH
    - Cost = $400-$1200
    - Mass = 10-30 kg
    - Volume = 9-26 L

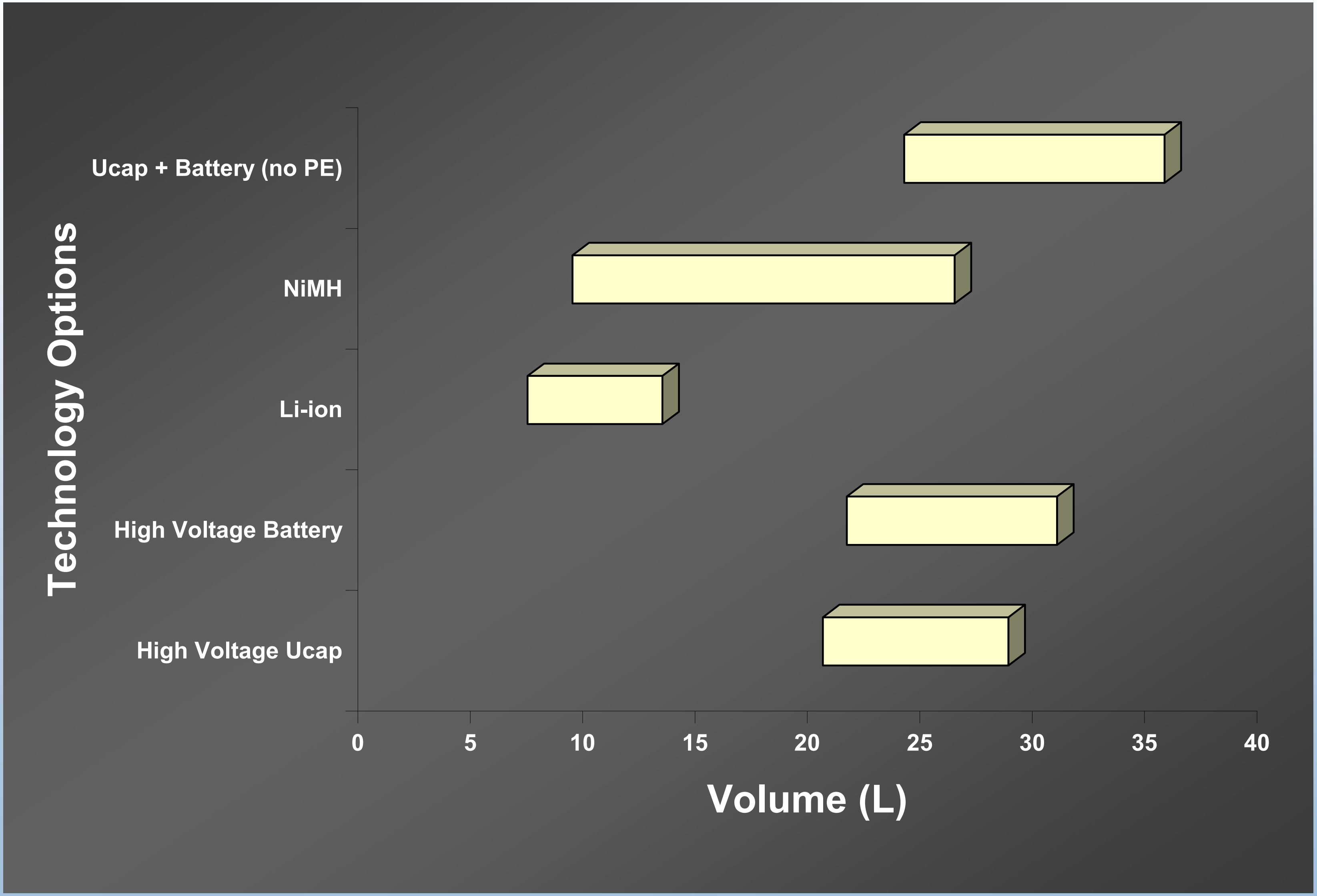
Cost Comparison



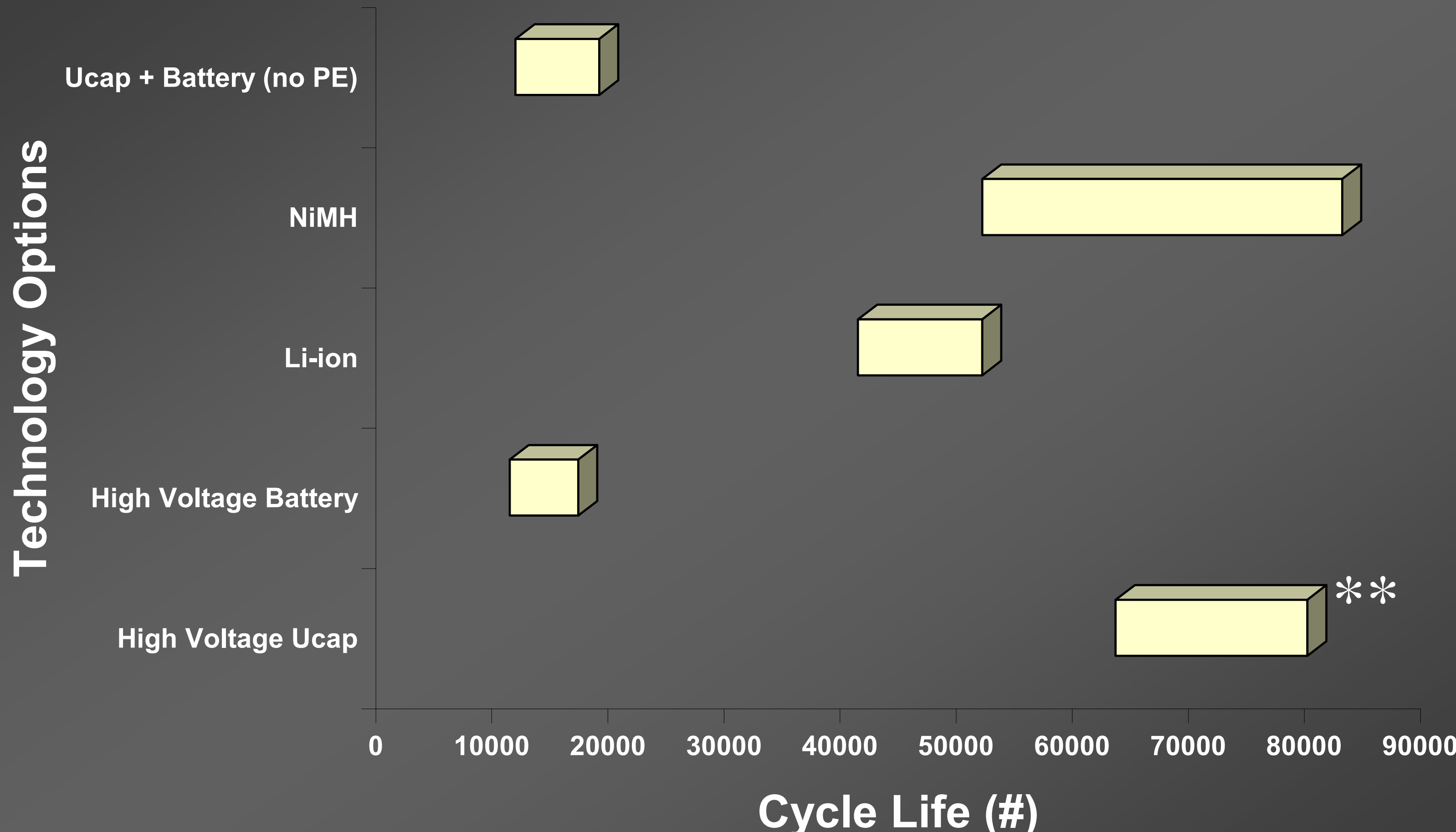
Mass Comparison



Volume Comparison



Cycle Life Comparison



**Note: UCap solution does not meet all performance requirements.

Observations and Summary

- Having a high voltage UCap based system seems to have less potential for minimizing the system cost. The fixed base part of the cost is large and the variable part is small.
- The fixed attributes of either PbA+UCap approach make them less attractive than other advanced energy storage technologies.
- If power electronics base costs can be cut in half and UCap costs go to 0.5 cents/F then these systems maybe competitive based on cost, less so on mass and volume.
- Incremental mass of PbA+UCap system is ~25kg and will result in ~1% decrease in fuel economy with all other things being equal.
- Operating efficiency of UCap and other technologies fairly similar. PbA significantly lower. Therefore, PbA+UCap system slightly less efficient than other technologies.
- Future work to include drive cycle analysis for particular vehicles

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