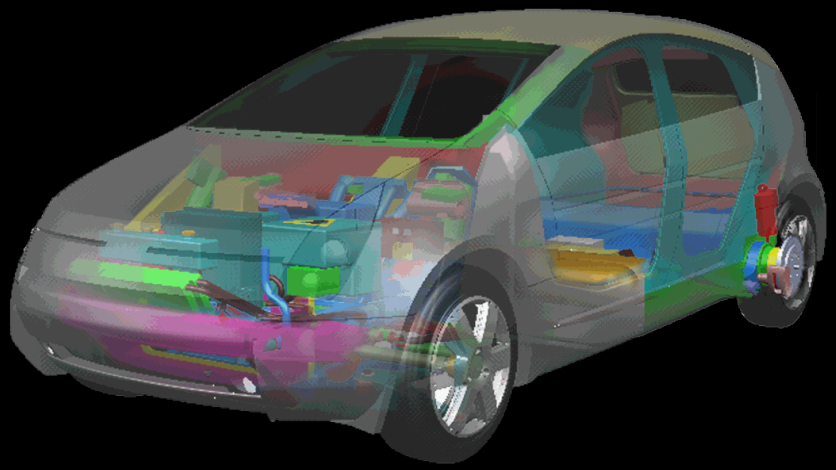

ROCKY MOUNTAIN
INSTITUTE

CNO's Naval-Industry R&D Partnership Conference 2003
Ronald Reagan Building, Washington, DC, 5 August 2003

More Fight, Less Energy, at Lower Cost!



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Transformational objectives

- Radically reduce the energy consumption of land, sea, and air platforms
- Increase their combat effectiveness, agility, deployability, and sustainability
- Reduce their capital and operating costs
- No compromise, no tradeoff

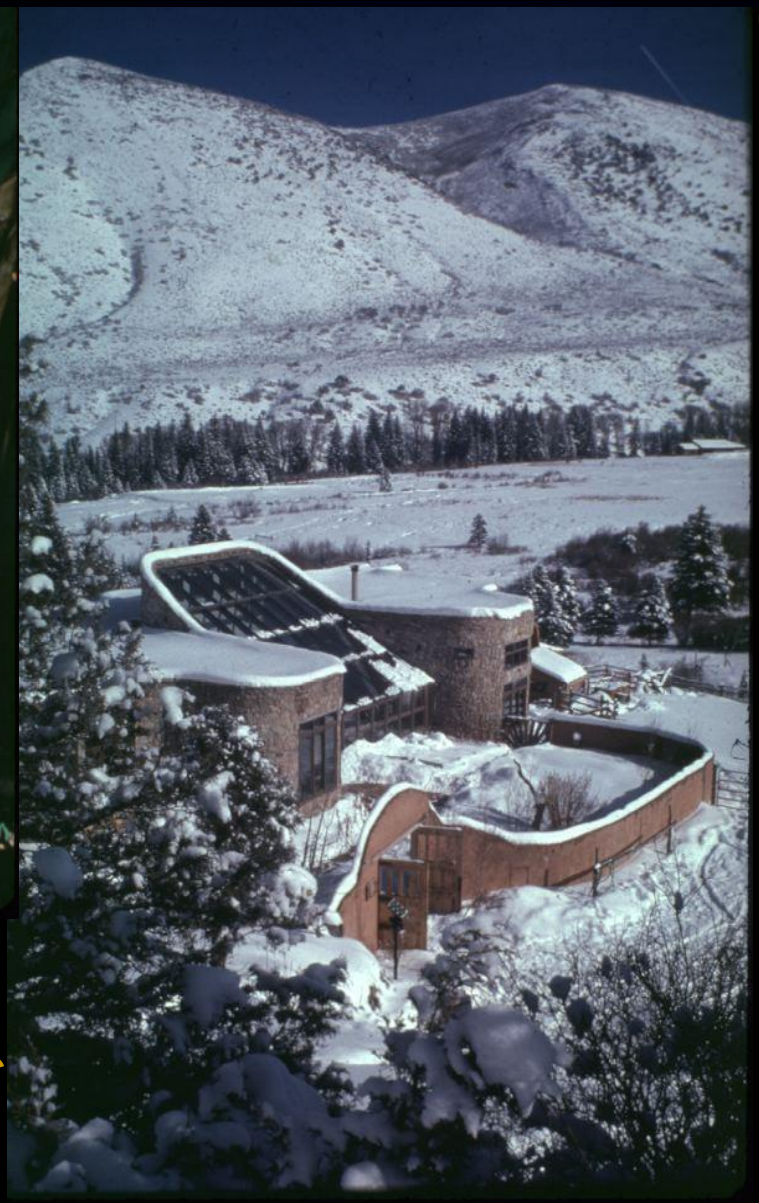
"If we are to achieve results never before accomplished, we must employ methods never before attempted." — Sir Francis Bacon

How can breakthrough design make big energy savings cost *less* than small or no savings?

Let's start with some building designs…

Rocky Mountain Institute

Grow bananas with no furnace at –44°C



- At 2200 m nr Aspen
- "Winter and July," frost any day, 39-d midwinter cloud
- Integrated design
- Superinsulated: k-0.05 W/m^{2}K roof, -0.14 walls, -0.47 to -0.7 [COG] glazings, air-to-air heat exchangers
- Thermally passive, 95% daylit
- Superefficient lts/eqt

Savings (1983 tech.):

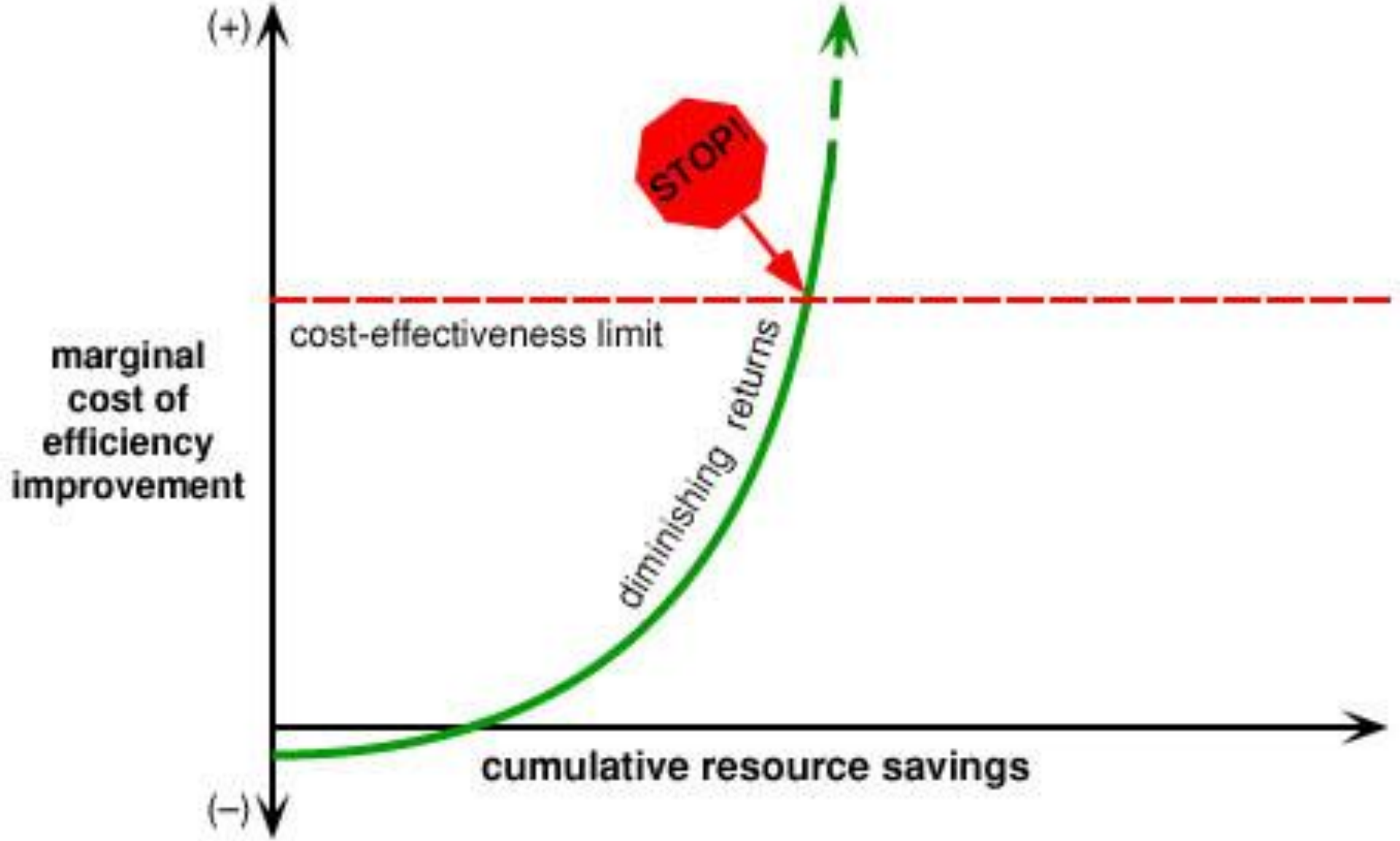
- 90% in home el. (~120 W_{av}/372 m^2)
- 99% in space & water heating
- 10-month payback, would be ≤0 now

PG&E ACT^2 House

Davis, California

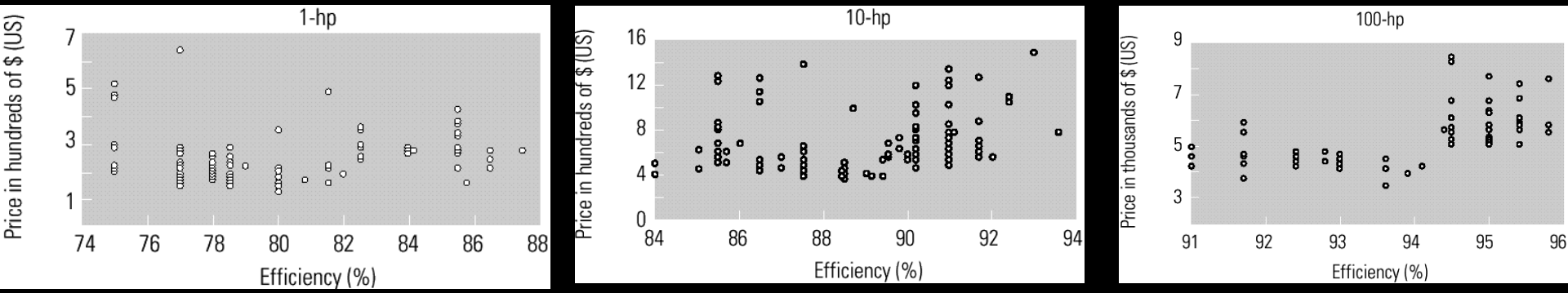
- ◇ Comfort without air conditioning at +45°C, even in 3-day heat storm
- ◇ Mature-market building cost $1,800 lower
- ◇ Present-valued maintenance cost $1,600 lower
- ◇ Original design's energy use ~82% below California Title 24 standard (1992)
- ◇ Last 7 improvements justified by savings of energy *plus* capital cost (last 1.5 T of a/c), not of energy alone
- ◇ Saved 3/4 of wall wood
- ◇ Later done at 46°C too

New design mentality: turn diminishing returns...



High efficiency doesn't always raise even components' capital cost

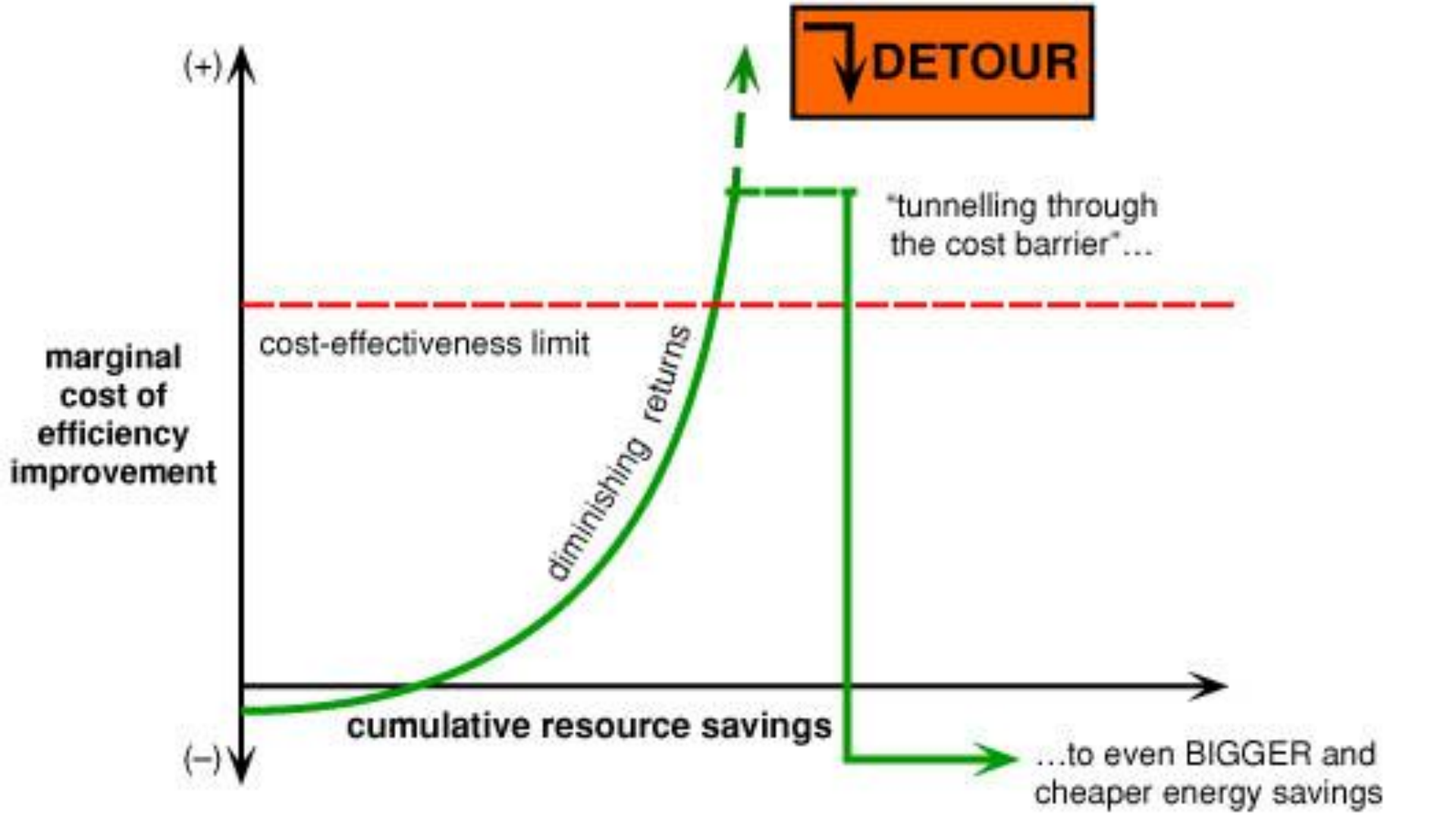
- Motor Master database shows no correlation between efficiency and trade price for North American motors (1,800-rpm TEFC Design B) up to at least 220 kW



E SOURCE (www.esource.com) **Drivepower Technology Atlas**, *1999, p 143, by permission*

- Same for industrial pumps, most rooftop chillers, refrigerators, televisions,…
- "In God we trust"; all others bring data

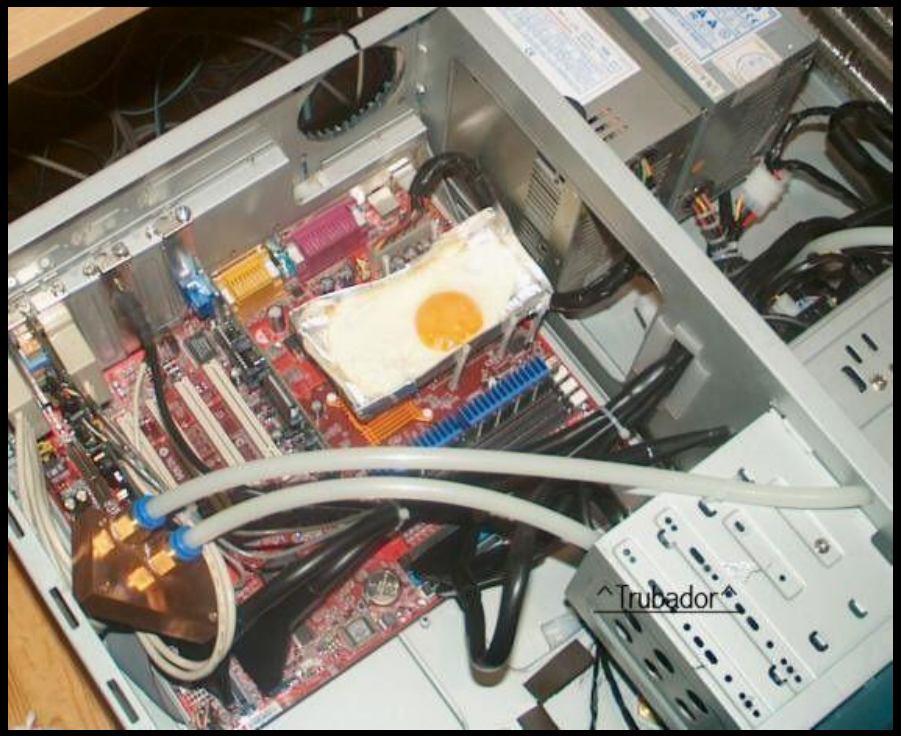
...into expanding returns: "tunneling through the cost barrier"



Examples of industrial opportunities

- Save half of motor-system electricity with retrofit aftertax ROI ~100–200%/y — buy 7 improvements, get 28 more as free byproducts
- Similar ROI saving >50% of chip-fab HVAC
- Top-efficiency refinery retrofit: save 42%, 3-y payb.
- North Sea oil platform: save half el., recover the rest
- Major LNG plant: enormous savings evident
- New supermarket: save ~70–90%, cost ?less
- New chemical plant: save 3/4 el. and 10% capex without any process changes such as microfluidics
- New data center: save 89%, cost less, higher uptime

Frying an egg on an Athlon XP1500+ in 11 minutes



From Trubador, www.handyscripts.co.uk/egg.asp

Simple RMI server substitution

- RMI replaced three (could have replaced four) WinNT servers with one small NetWinder Linux box (now model 3100)
- Nominal power 14 W, no fan
- Faster and more capable than NTs
- Hardware plus software cost less than NT license fee on replaced NT boxes
- 98–99% energy saving
- Big space saving
- Now imagine this aboard a Naval vessel — avoiding extra power and cooling capacity…

1U Wintel rack-mounted server

- 800 MHz Intel processor
- 19"×30"
- Disk drives, I/O ports, memory
- Floppy drive
- CD ROM
- Video capabilities
- Serial / parallel ports
- PCI expansion slots
- 160 Watt power supply; often runs at lower power, with disproportionately lower power-supply efficiency
- 9 fans using ~20–25% of total server power
- $2000+

This and following slide courtesy of Chris Hipp, ex-RLX

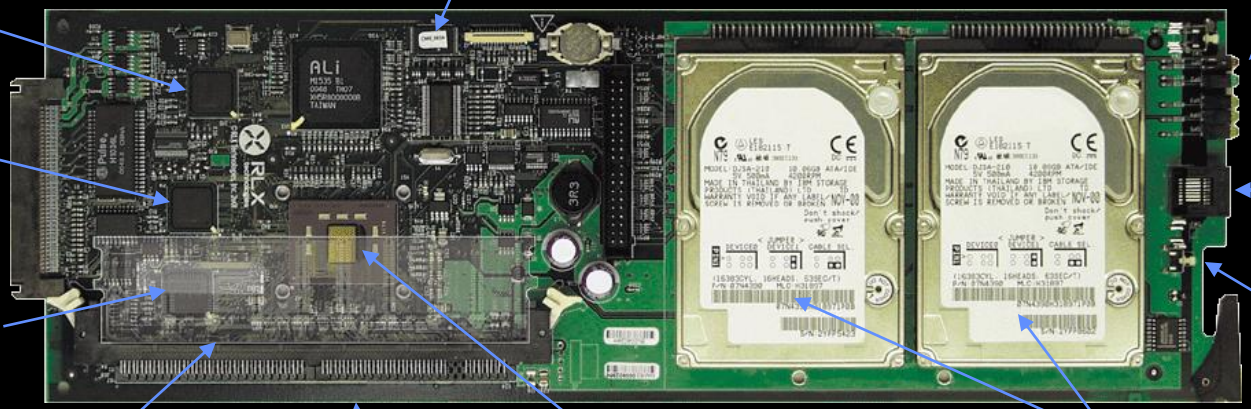
RLX ServerBlade™, ~15.7 W

- **Public NIC**
- **33 MHz PCI**

Private NIC
33 MHz PCI

Management NIC
33 MHz PCI

CMS 1 MB



Status LEDs

Serial RJ-45
debug port

Reset Switch

128MB, 256MB, 512MB
DIMM SDRAM
PC-133

512KB
Flash ROM

Transmeta™
TM5600 633 MHz

Crusoe™

128KB L1 cache, 512KB L2 cache
LongRun, Southbridge, X86 compatible

ATA 66
0, 1 or 2 - 2.5" HDD
10 or 30 GB each

72 blade servers in 9U

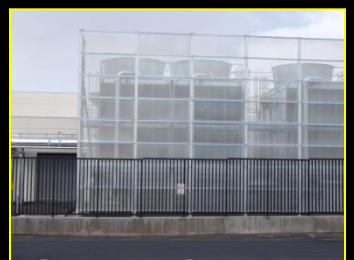
Wu-chun Feng's Green Destiny supercomputer, LANL

◇ RLX passively-cooled blade servers using TransMeta Crusoe CPU: 8× denser, 5–8× less power-intensive than Wintel

◇ Up 100%/≥9 mo in an uncooled 31°C warehouse

◇ ~7–8× better energy efficiency (in an iterative science app), ~65–75% lower total cost of ownership; ~160 peak Gflops but wins on calcs > MTBF

◇ Pay ~50–75% more for the bare hardware (at least at early blade prices) but ~90% less for power and cooling, space, downtime, and system administration

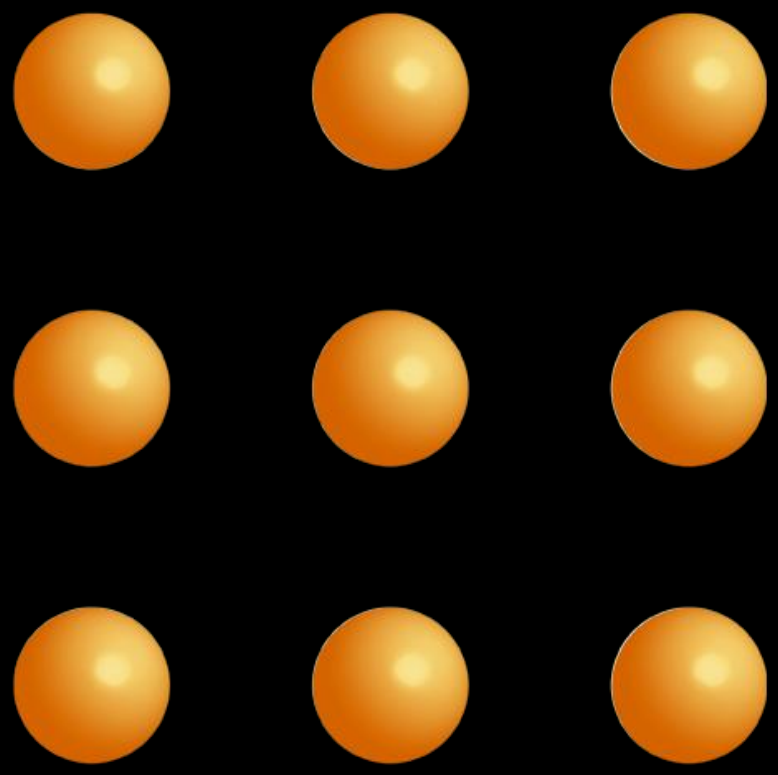


Compare LANL Q supercomputer's cooling towers

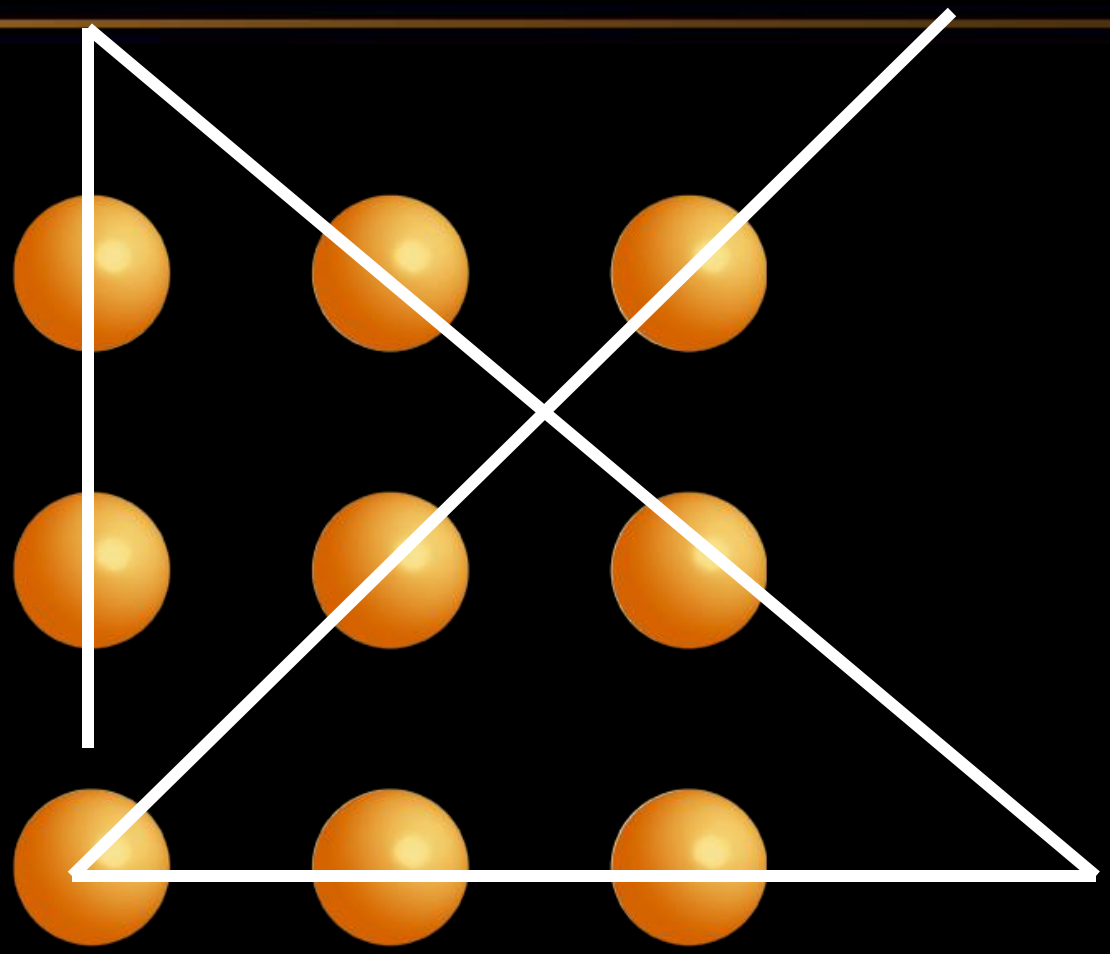
Edwin Land

"People who seem to have had a new idea have often just stopped having an old idea"

The Nine Dots Problem



The Nine Dots Problem



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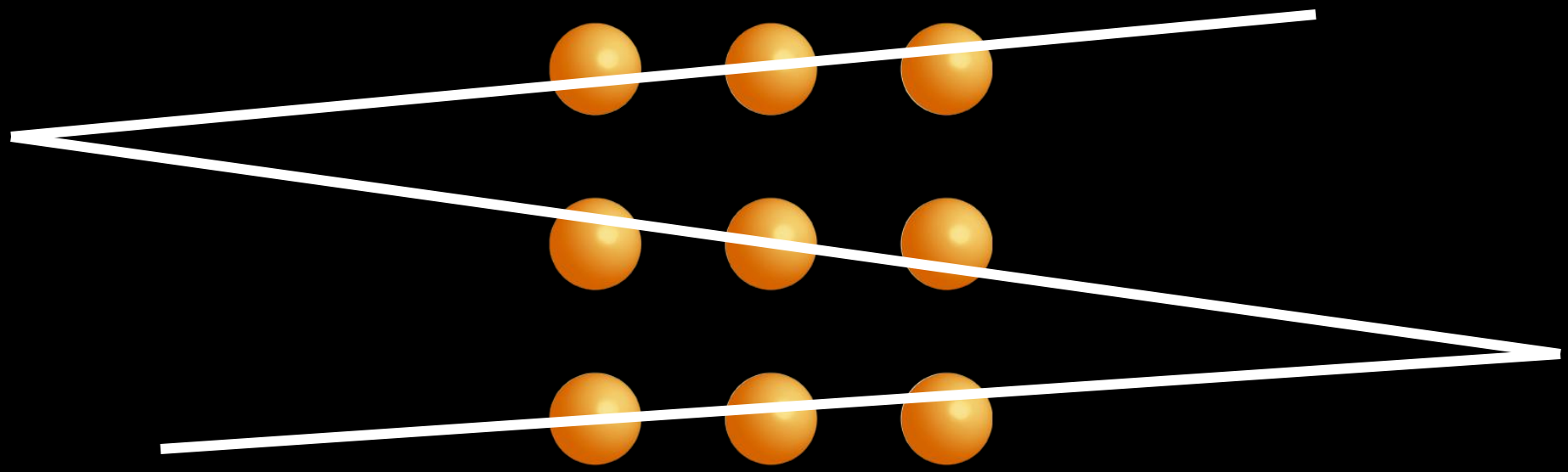
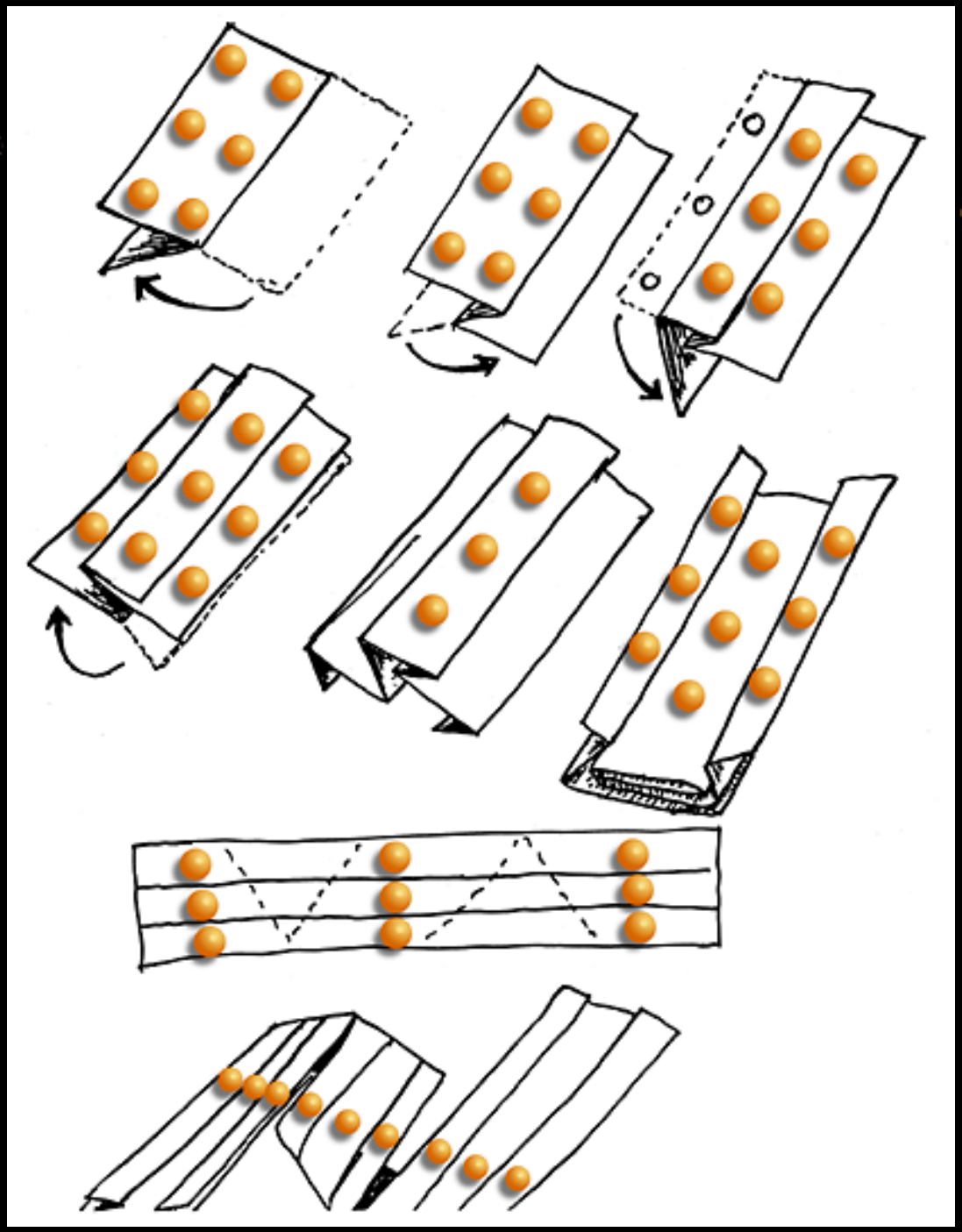
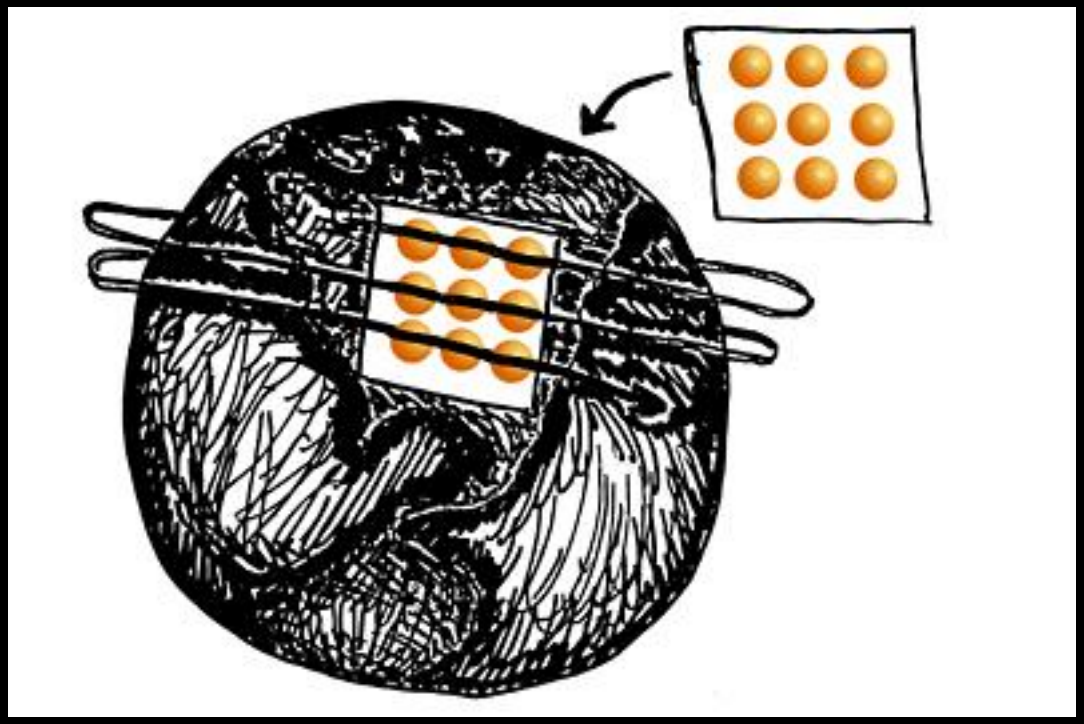


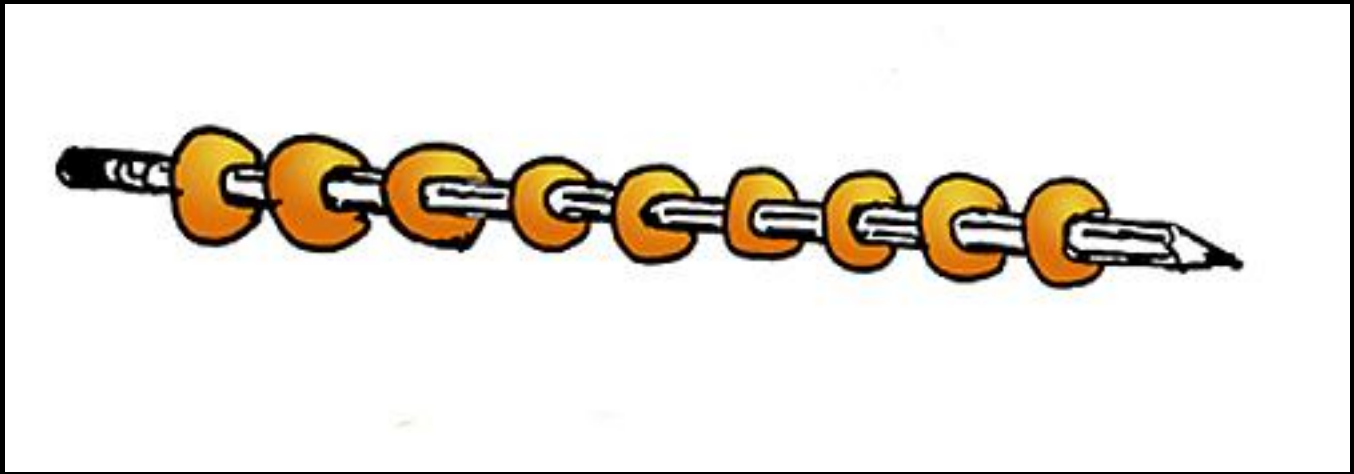


origami solution

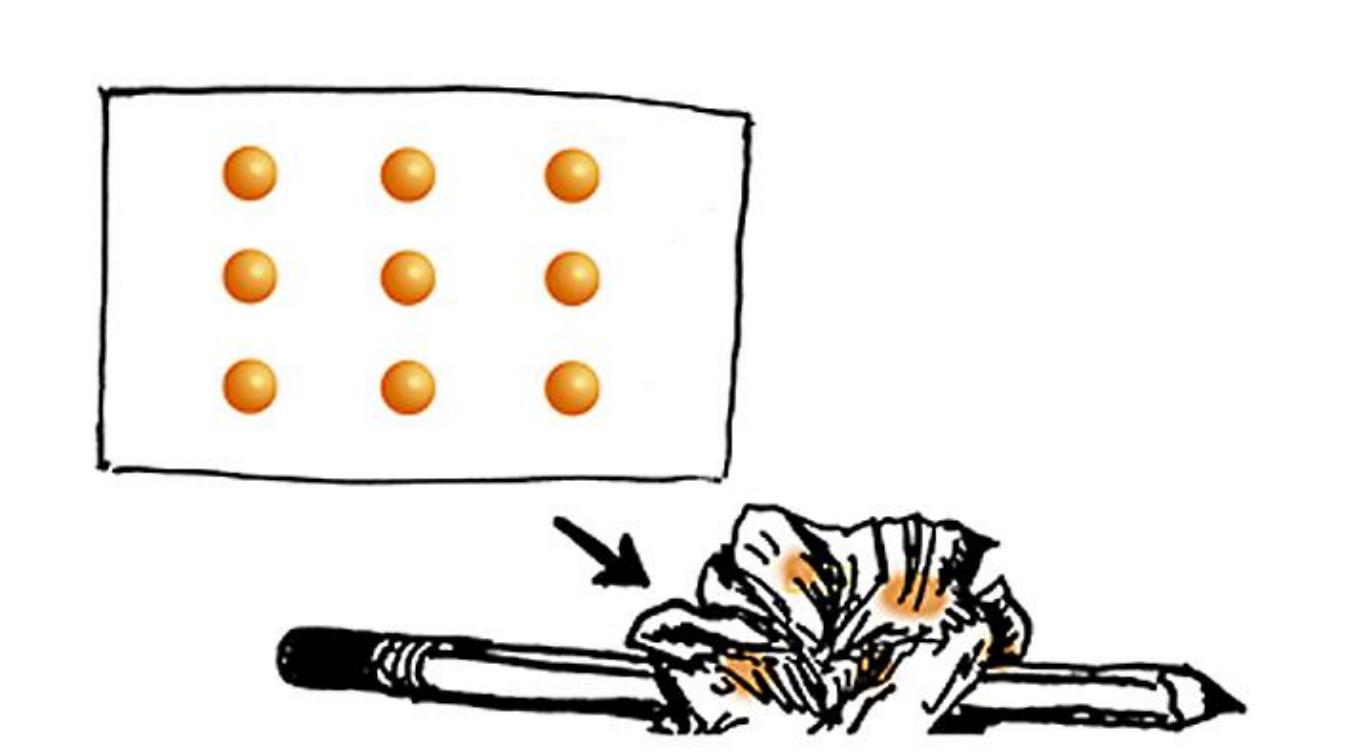
geographer's solution

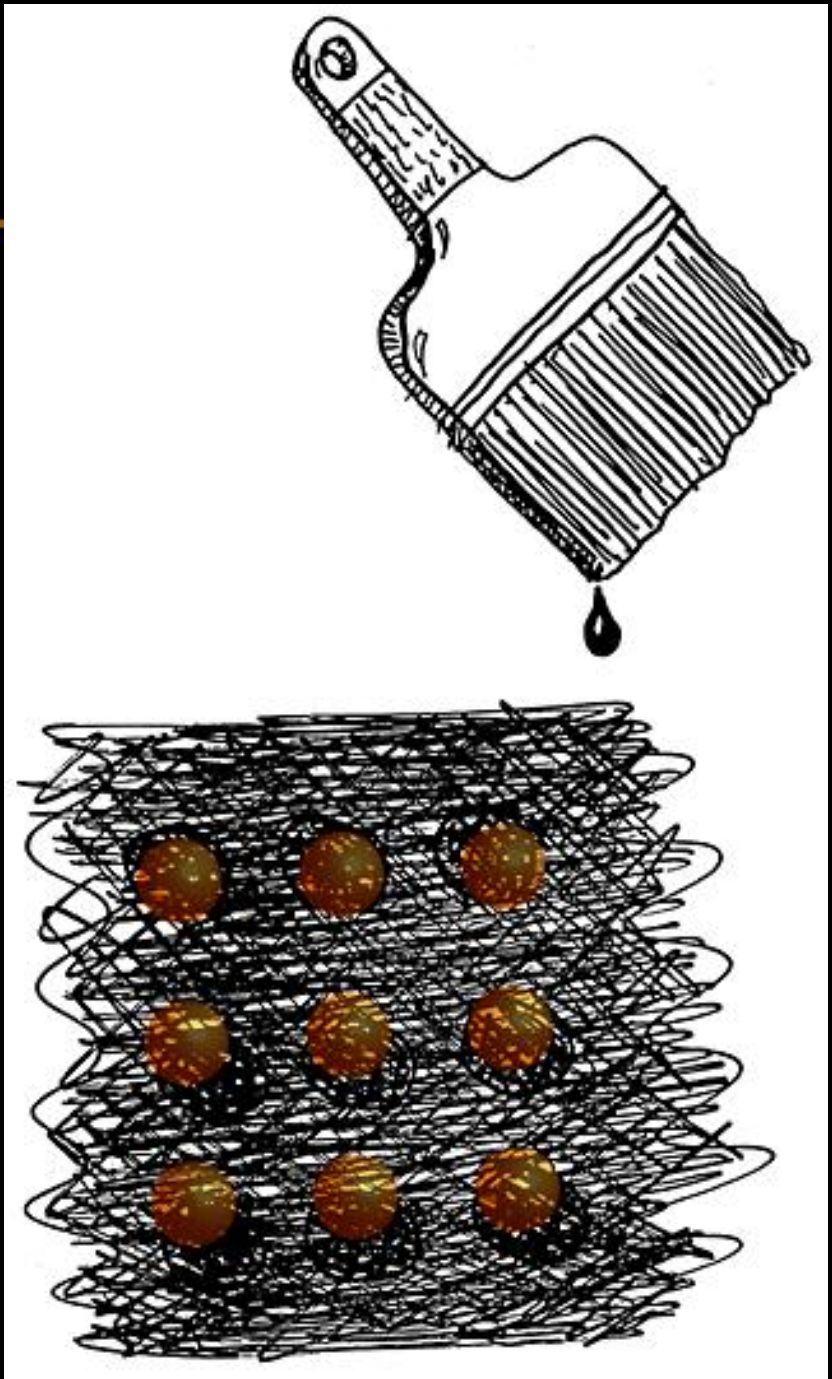


mechanical engineer’s solution



statistician's solution





wide line
solution

Edwin Land

Invention is "… a sudden cessation of stupidity"

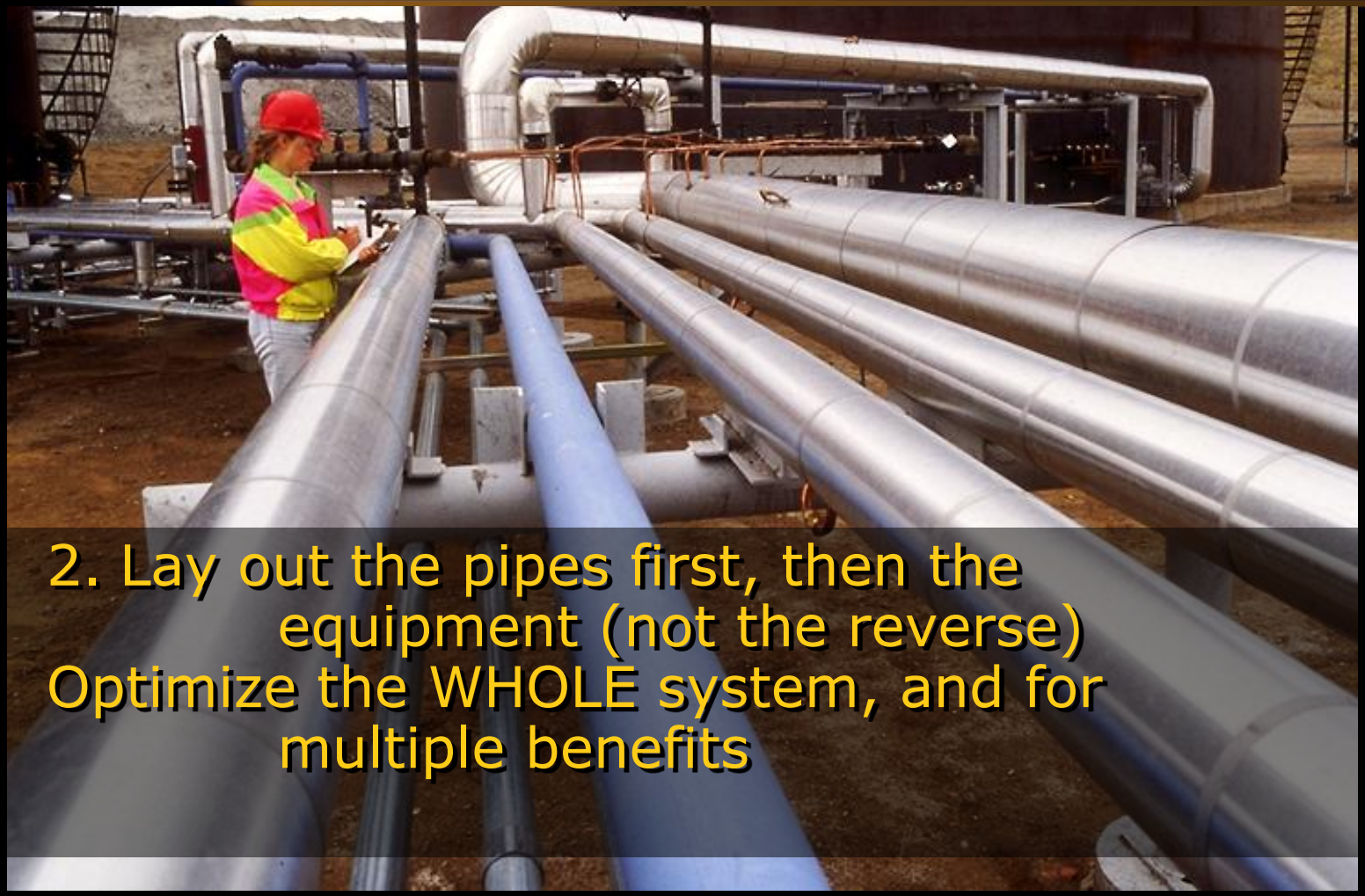
New design mentality

- Redesigning a standard (supposedly optimized) industrial pumping loop cut power from 70.8 to 5.3 kW (–92%), cost less to build, and worked better
- Just two changes in design mentality

New design mentality, an example

1. Big pipes, small pumps (not the opposite)

No new technologies, just two design changes



2. Lay out the pipes first, then the equipment (not the reverse)

Optimize the WHOLE system, and for multiple benefits

No new technologies, just two design changes

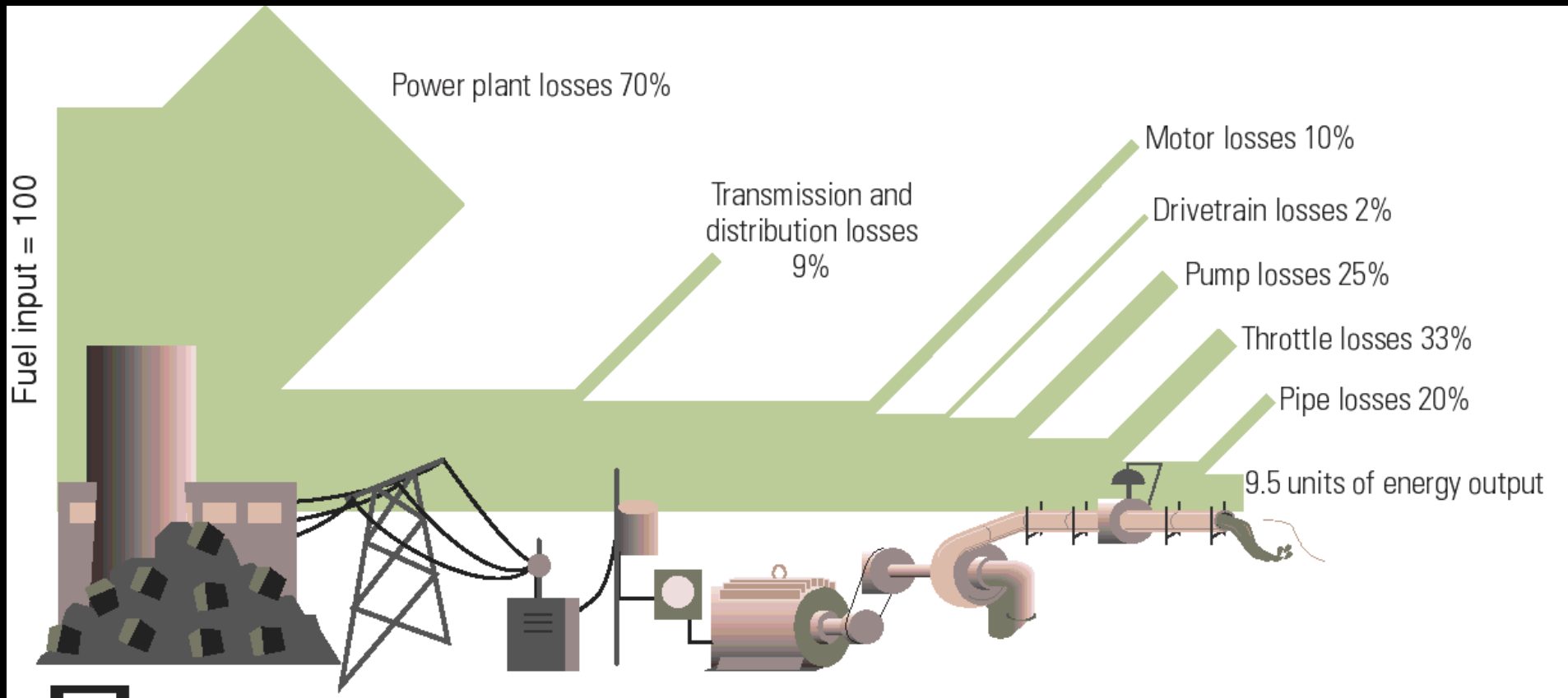
- Fat, short, straight pipes — not skinny, long, crooked pipes!
- Benefits counted
  - 92% less pumping energy
  - Lower capital cost
- "Bonus" benefit also captured
  - 70 kW lower heat loss from pipes
- Additional benefits not counted
  - Less space, weight, and noise
  - Clean layout for easy maintenance access
  - But needs little maintenance — also more reliable
  - Longer equipment life
- If counted, we'd have saved more…maybe ~98%

New design mentality: why this example matters

- Pumping is the biggest use of motors
- Motors use 3/5 of all electricity
- Saving one unit of friction in the pipe saves 10 units of fuel at the power plant
- This is archetypical: applying whole-system design principles to almost *every* technical system yields ~3–10x energy/resource savings, and usually costs less to build, yet improves performance
- We need a pedagogic toolkit of diverse examples…for the nonviolent overthrow of bad engineering (RMI's 10XE project)

The leverage of downstream savings: pipes and pumping

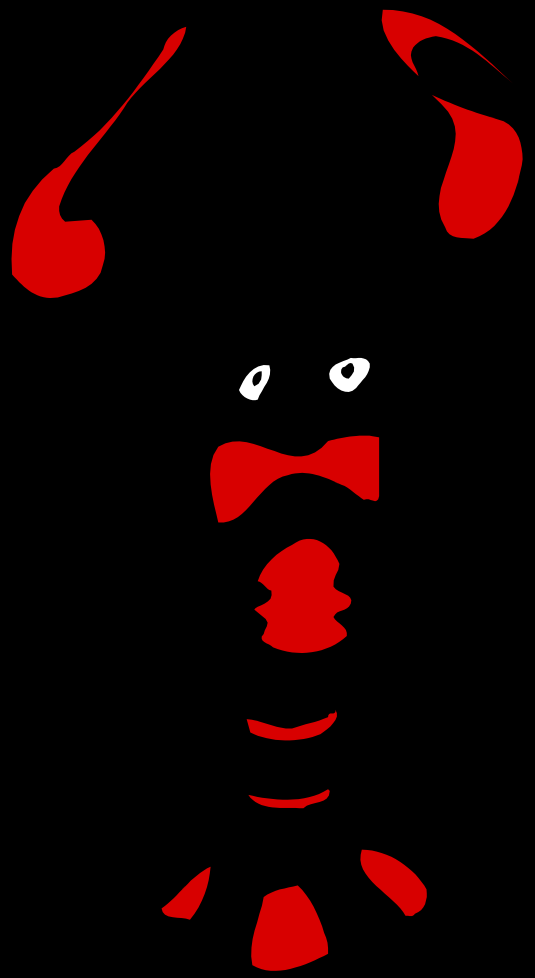
- Compounding losses require ~10 units of fuel at the power plant to produce 1 unit of flow in the pipe — ~20 with GTGs!



From the *Drivepower Technology Atlas*.
Courtesy of E SOURCE, www.esource.com.

Eating the Atlantic lobster

- Big, obvious chunks of meat in the tail and the front claws
- A roughly equal quantity of tasty morsels hidden in crevices, requiring skill and persistence to recover
- Go for both
- Mmmmm!



The right steps in the right order: space cooling

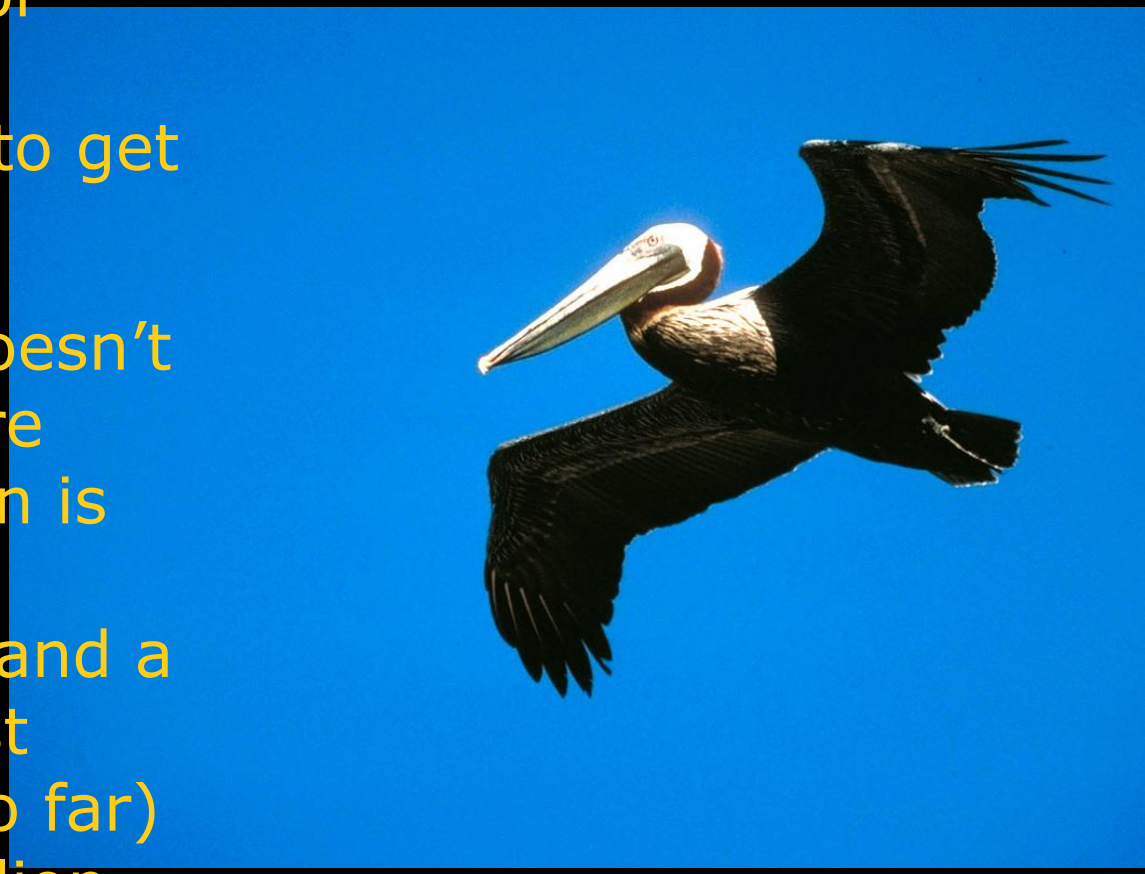
1. Expand comfort envelope
2. Minimize unwanted heat gains
3. Passive cooling
   - Ventilative, radiative, ground-/groundwater-/seawater-coupled
4. Active nonrefrigerative cooling
   - Evaporative, desiccant, absorption, hybrids: COP ≥100
   - Direct/indirect evaporative + VFD recip in CA: COP 25
5. Superefficient refrigerative cooling: COP 6
6. Coolth storage and controls
7. Cumulative energy saving: ~90–100%, better comfort, lower capital cost, better uptime

The secret of great design integration:

No Compromise!

Design is *not* the art of compromise and tradeoff—how not to get what you want

J. Baldwin: "Nature doesn't compromise; nature optimizes. A pelican is not a compromise between a seagull and a crow." It is the best possible pelican (so far) — and after 90 million years, that's a pretty good one



The need for compromise is generally a symptom of misstated design intent

More Capable Warfighting Through Reduced Fuel Burden

- Defense Science Board Task Force report 1/01, released 5/01; chaired by VADM Richard Truly (Ret.)
- DoD spends 1/3 of its budget and 1/2 of its personnel on logistics, mostly moving fuel (~70% of the Army's tons deployed in Desert Storm)
- Most of that fuel could be saved, but isn't; why?
- Platform designers assume logistics is free!
- E.g., tank designers assume the Defense Energy Support Ctr. fuel price ($1.34/gal in FY02)—but quick delivery 600 km into theater (via 3-stage helicopter relay — not an unusual improvisation) adds ~$400–600/gal.
- Cost and warfighting both need efficient platforms
- The prize: ~$2–3b/y in avoidable direct fuel cost, + several times that in avoidable fuel logistics costs, redeployed assets, far more effective warfighting

DESC *vs.* true *delivered* DoD fuel cost per year

Service	DESC fuel cost FY99 @ $0.87/gal	Delivered fuel cost	Ratio	Omitted costs
Army	~$0.2b (1997; excl. energy used for deployment by Navy & Air Force)	$3.4b incl. 20k active POL @$100k/ y + 30k res POL @ $30k /y	16	POL equipment/facilities + combat fuel delivery
Navy	$1.6b (1997; excl. midair refueling by Air Force)	$2.5b	1.6	purchase of new oilers
Air Force	$1.8b	$4.4b	2.4	proposed new tankers (>$9b)
Total	$3.6b ($5+b FY02)	$10.3b (conservative!)	2.9	those plus pyramids of support costs

Source: Defense Science Board, *More Capable Warfighting Through Reduced Fuel Burden*, May 2001 (USD/AQT), at:

p. 39; omits indirect use by Navy and Air Force to deploy Army assets; omits ownership cost of equipment; ratio for delivery far beyond FEBA can be many hundreds

pp. 4, 20; delivery 70% by oiler @ $0.64/gal, 30% pierside @ $0.05/gal (Dr. Alan Roberts, pers. comm. 3 April 2001)

p. 17; includes total ownership cost of tanker fleet except purchase of >55 new tankers

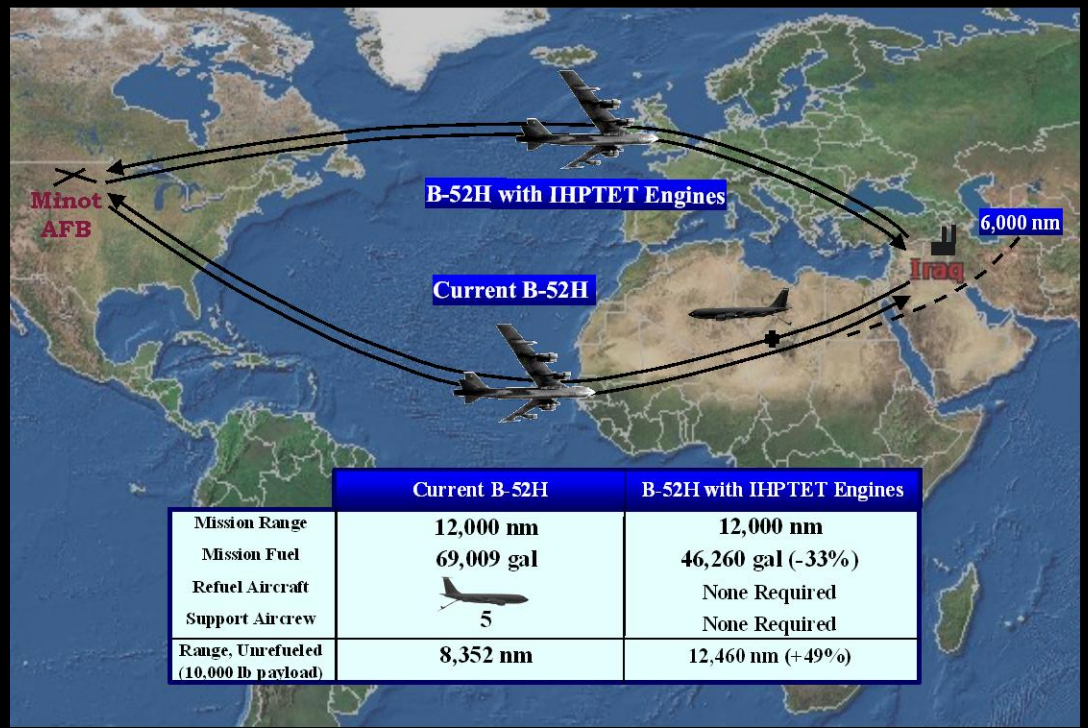
Delivered fuel cost would scale to ~$12–14b/y at FY02 DESC fuel price ($1.37/gal)—much more if all the omitted costs are counted

Reality check: DoD spends roughly a third of its budget on logistics, for which ≥60% of tonnage is fuel, so hypothetically saving half the fuel and then downsizing would be worth ~10% of DoD's budget, or ≥$30b/y, if logistics cost were proportional to tons and budget included only hauling (both assumptions probably false)

Typical misallocation of funds: Air Force

- B52H bomber: @ $1/gal, 1960s engines were felt not worth retrofitting (fuel –33%, range +28% to +49%); but retrofit looks great, counting just 10% midair refueling, @ $17.5/gal—and then midair re-fueling is seldom necessary (Minot⌦Iraq on one fill)!

Benefits of B-52H Efficiency Improvements



	Current B-52H	B-52H with IHPTET Engines
Mission Range	12,000 nm	12,000 nm
Mission Fuel	69,009 gal	46,260 gal (-33%)
Refuel Aircraft		None Required
Support Aircrew	5	None Required
Range, Unrefueled (10,000 lb payload)	8,352 nm	12,460 nm (+49%)

A prompt engine upgrade (vendor-financed?) might save tanker cost in current budget, pay for PGM upgrade; DSB panel unan'y. recommended 4/03 est'd $6–9b sav.

Typical misallocation of funds: Army

- M1A2 tank: late-1960s gas turbine, 1500 hp to sprint 68 tons around the battlefield at 30 mph, idles ~60–80+% of the time at <1% efficiency to run a 5-kW hotel load: no APU, for two reasons
  - Designers calculated 46-y payback @ ~$1/gal; but it's 3.5 y at *delivered* peacetime fuel cost ($13/gal), ~1 month in wartime (up to $400–600/gal delivered)
  - No room under armor…so just strap it on the back! If it gets shot away, you're just back to current situation.

Today's Top 10 Battlefield Fuel Users

SWA scenario using current Equipment Usage Profile data

Of the top 10 Army battlefield fuel users, only #5 and #10 are combat platforms

1. **Truck Tractor: Line Haul C/S 50000 GVWR 6X4 M915**
2. **Helicopter Utility: UH-60L**
3. **Truck Tractor: MTV W/E**
4. **Truck Tractor: Heavy Equipment Transporter (HET)**
5. ***Tank Combat Full Tracked: 120MM Gun M1A2***
6. **Helicopter Cargo Transport: CH-47D**
7. **Decontaminating Apparatus: PWR DRVN LT WT**
8. **Truck Utility: Cargo/Troop Carrier 1-1/4 Ton 4X4 W/E (HMMWV)**
9. **Water Heater: Mounted Ration**
10. ***Helicopter: Attack AH-64D***

Italics indicates combat systems.
Source: CASCOM study for DSB using FASTALS for SWA.
The end-state force list for SWA (based on the FASTALS Deployment Report) was used as the force structure.

Of the top ten Army battlefield fuel users, #5 is the tank, #10 is the Apache helicopters; the other 8 are noncombatants, several of which...haul fuel!

Army After Next fuel efficiency simulation*

- Based on M1 Series AAN fuel saving of 89%
- AAN saves 3,942 POL personnel, 1,155 maintenance, 4,179 other (Σ = 9,276); 228 cargo trucks, 219 line haul trucks, 30 util trucks, 68 MHE, 89 gensets; 106,477 tons fuel in division base area + 128,334 tons in brigade area; not counting upstream logistics to deliver fuel & associated assets into theater
- Total saving: up to 20,000 POL personnel and their equipment, plus more upstream
- Total fuel use = AOE – 60%; ≥75% "easily" w/improved tactics & info-dominance gains

*Based on CASCOM FASTALS w/TAA 05 MTW West (NEA) Baseline; no Army XXI or AAN Op Tactics, Techniques, or Procedures included; constant mission, same battle outcome; per LTC Ronald Salyer, USARL, 757/864-7617, 17 Aug 1999 brief to Defense Science Board panel, c/o panel member A B Lovins, CEO, RMI, & Chairman, Hypercar, Inc.

Typical misallocation of funds: Navy

- As of 2001, stern flaps, paying back in ~1–2 years, were retrofitted on 12 hulls (saving ~$2M/y), with 48 more planned (+ $8M/y), but should have been on 58 more (+ $10M/y); costs and benefits show up on different budgets, splitting the incentive
- Navy is the only Service that assessed delivered fuel cost (until 1994—then NAVSEA stopped)
- Comptroller let(s?) PACFLT (only?) skippers keep part of operational fuel savings, correcting the split incentive
- FY99 savings ($23M) is <1/2 of NAVSEA's min. potent'l.
  - *E.g.*, optimal power setting cuts fuel by ~10–20%, up to ~65%
- Design practice and pedagogy can be much improved in ships, just as NAVFAC did in facilities starting in 1995

An encouraging example of breakthrough design

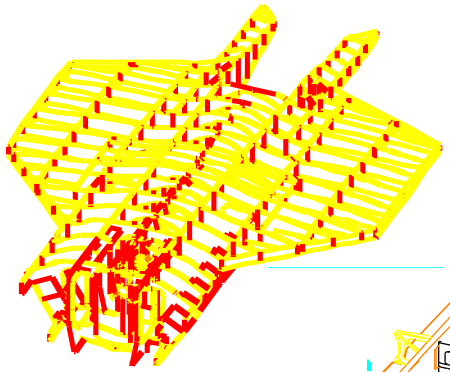
- At the Lockheed Martin Skunk Works®, engineer David Taggart led a team that designed an advanced tactical fighter-plane airframe…
  - made 95% of carbon-fiber composites
  - 1/3 lighter than its 72%-metal predecessor
  - *but 2/3 cheaper*…
  - because it was designed for optimal manufacturing from carbon, not from metal
- As VP Product Development and CTO of Hypercar, Inc., he then did much the same for cars — showing what happens when cars are designed around a breakthrough composites manufacturing technology (Fiberforge™) now being validated (85–90% perf. @ 10–20% cost)

Integrated Technology for Affordability (IATA)

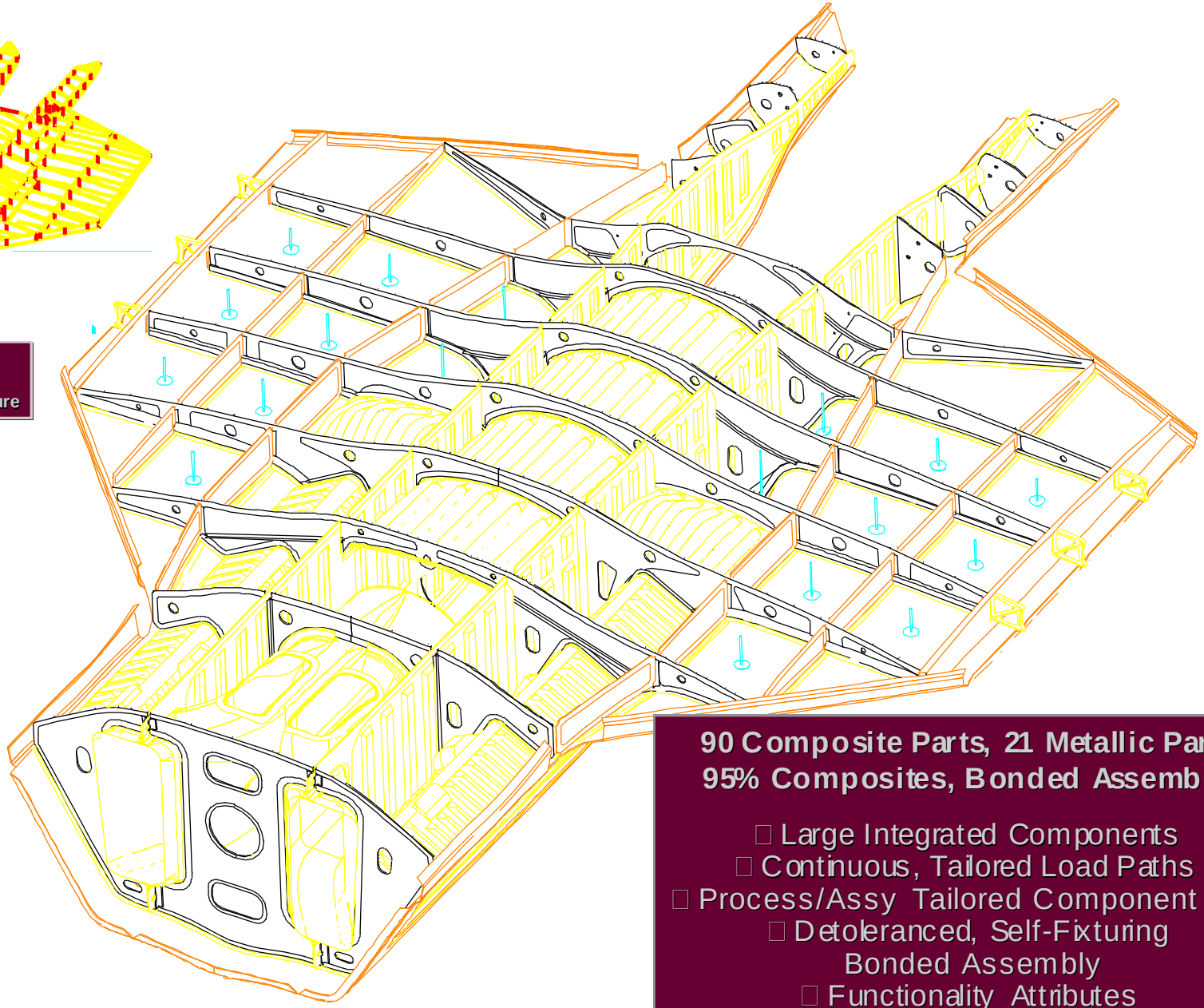
- DARPA funded effort (1994–96)
- The challenge: Airframes must provide performance **affordably**
- What was needed: A ***Breakthrough*** cost reduction compared to c
  INTEGRATED AIRFRAME TECHNOLOGY FOR AFFORDABILITY
  ARPA • AIRFORCE • SKUNK WORKS
  airframe technology
- Proposed solution: Design—create a new paradigm
- Lockheed Martin Skunk Works, Alliant Techsystems, Dow-UTC, AECL
- Focus: JSF

This and next 6 slides from D.F. Taggart brief to DSB, 20 Sept 2000

IATA Preferred System Concept



JAST/ASTOVL
Config. 140:
Conventional Structure

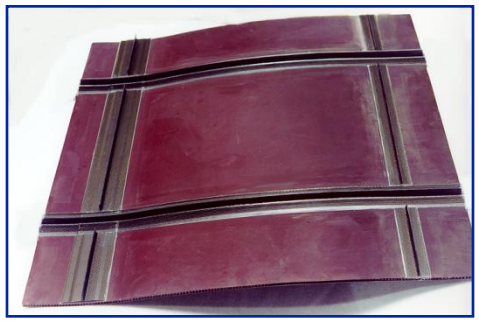


90 Composite Parts, 21 Metallic Parts
95% Composites, Bonded Assembly

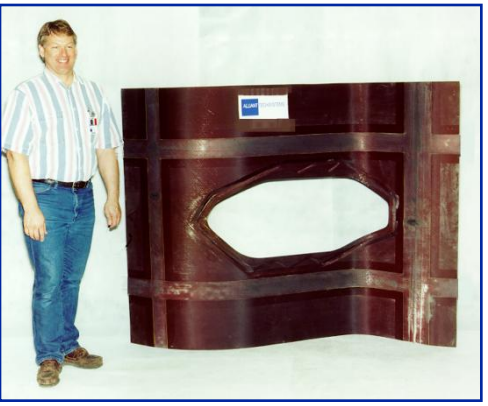
- Large Integrated Components
- Continuous, Tailored Load Paths
- Process/Assy Tailored Component Design
- Detoleranced, Self-Fixturing Bonded Assembly
- Functionality Attributes

Process Demonstration Assembly

- *Full Scale: 5 ft x 5 ft x ft section*
- *Envisioned Production Processes*
- *Most complex, highly loaded section*



Fiber Placed Upper/Lower Skins
- E-beam Cured: Cationic Resin
- Co-Cured Large Cell Core
- Alliant TechSystems

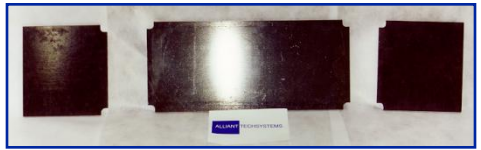


Bonded Assembly
- Detoleranced
- Self-Fixturing

RTM Spar/Bulkheads
- Tailored Load Paths
- PR500 Epoxy
- DOW-UT

VARTM Keelson
- E-beam Cured: Cationic B/C
- Skunk Works / AECL

Hand Lay-up Ribs
- Thermoset Materials
- Alliant TechSystems



Critical Technology Areas

- Fastenerless Assembly
- Skin Stabilization Approaches
- Integral Hard Points
- Battle Damage Survivability
- High Temperature Structure
- Integral, Fully Bonded Fuel Cells (and Structure)
- R, M, & S Culture / Issues
- E-Beam Technology

Benchmark Comparison to Baseline

Components, Weight

Non-Recurring Tooling, Planning

Recurring Fabrication

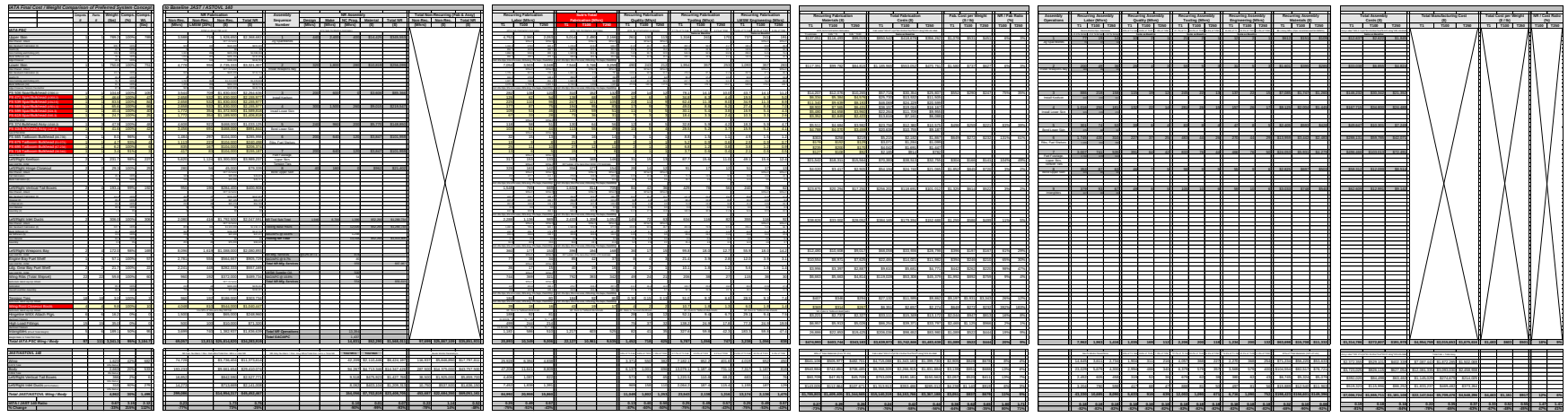
Fabrication Summary

Recurring Assembly

Production Summary

IATA PSC

JAST/ASTOVL 140



Fab, Assy, Procurement

Labor, QA, Tooling, Eng., Materials

Labor, QA, Tooling, Eng., Materials

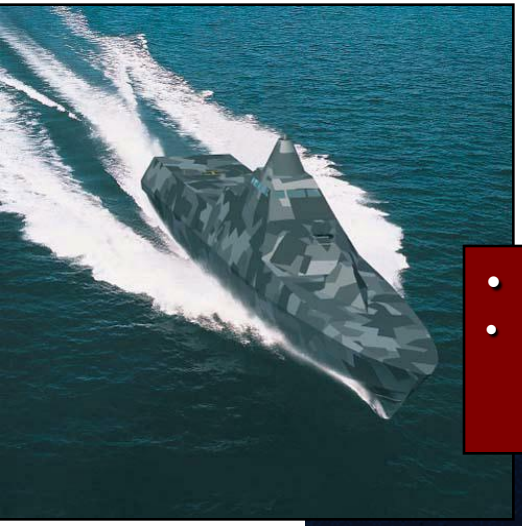
- IATA Production Costs: Bottoms-Up NR, Recurring QA, Matls, Fab, Assy, and Weight
- Baseline Production Costs: Parametric Historical Database Based on Weight
- Assumptions:
  - 4 AC/month, 100-1000 Total AC over 10 years
  - Assume Development Program Completed, Facilities Exist
  - Same Rates Applied to IATA and 140 Manhours
  - IATA Subs Estimated Fab, Skunk Works Estimated Assy

Benchmark Comparison to Baseline

IATA Final Cost / Weight Comparison of Preferred System Concept to Baseline 140							
	Weight (lbs)	Total Recurring Production Cost ($)			Total Cost per Weight ($ / lb)		
		T1	T100	T250	T1	T100	T250
Total IATA PSC Wing / Body	3,341.3	$5,004,231	$2,023,334	$1,680,545	$1,498	$606	$503
Total JAST/ASTOVL Wing / Body	4,962	$22,147,044	$5,709,476	$4,548,296	$4,463	$1,151	$917
IATA / JAST 140 Ratio	0.67	0.23	0.35	0.37	0.34	0.53	0.55
% Change	-33%	-77%	-65%	-63%	-66%	-47%	-45%

- **90 Composite Components, 21 Metallic**
- **65% Reduction in T100 Rec. Production Costs** ($3.68M savings)
- **48% Reduction in Non-Recurring Production Costs** ($30.2M savings)
- **33% Reduction in Weight** (1621 lbs savings)
- **95% Composites** (vs 30% in Baseline)
- **Orders of magnitude part count reduction**
- **Conservative PSC Estimates:**
  - 6% “Intangible” Cost and Weight Added to PSC
  - Full Recurring Engineering Added to PSC
  - Full Extent of E-beam Cost Advantage Not Included
  - No Credit for Material Forms to Enhance Producibility
- **Commensurate Reductions in LCC Anticipated**

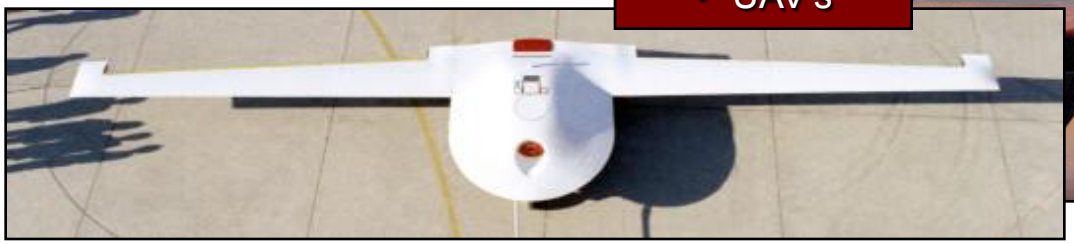
Applicability?



- Naval Vessels
- Embedded EMS
- Fast Attack
- OPV's

- Land Vehicles
  - Survivability
  - Endurance
  - Mobility

- Air vehicles
  - Prototypes
  - UAV's



5×-efficiency, no-oil, same-cost, mid-size SUV (see 1615 breakout session)

an illustrative, costed, manufacturable, and uncompromised concept car (11/2000) developed with internal funding by a small firm, Hypercar, Inc. (www.hypercar.com), on time and on budget, with attributes never previously combined in one vehicle

- seats 5 comfortably, up to 1.96 m^3 cargo
- hauls 1/2 ton up a 44% grade
- 857 kg (47% mass of Lexus RX300)
- head-on wall crash @ 56 km/h doesn't damage passenger compartment
- head-on collision with a car 2× its mass, each @ 48 km/h, prevents serious injury
- 0–100 km/h in 8.3 seconds
- 2.38 L/100 km (99 mpg-equiv,5× RX300)
- 530 km on 3.4 kg of 350-bar H_2 gas
- 89 km/h on just normal air-cond. energy
- zero-emission (hot water)
- stiff, sporty, all-wheel fast digital traction
- ultra-reliable, software-rich, flexible
- wireless diagnostics/upgrades/tuneups
- 320-Mm warranty;no fatigue, rust, dent
- competitive manufacturing cost expected
- decisive mfg. advantages—≤10× less capital, space, assembly, parts count
- production rampup feasible ~2007–08

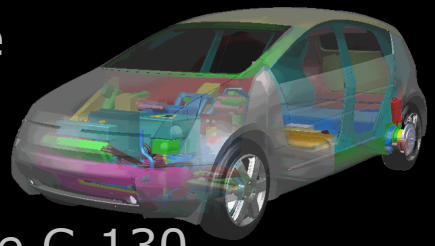
Ultimate public benefits of quin-tupled light-vehicle fuel efficiency

- Oil savings: U.S. potential = 8 Mbbl/day = 1 Saudi Arabia = 42 Arctic National Wildlife Refuges; world potential = 1 nega-OPEC; hence nega-missions in the Gulf (Mission Unnecessary)
- Decouple driving from climate change and smog
  - Profitably deal with ~2/3 of the climate challenge
- Lead a fast transition to a hydrogen economy
  - Can be profitable at each step; adoption already starting
- Parked cars serving as plug-in "power stations on wheels" when parked, recovering much or most of their capital cost from electric revenues

"We'll take two." — *Automobile*, November 2001

Leapfrogging military transformation: an Army example

1. M1A2 tank: 68 T, ~0.56 mpg, peerless fighting machine but nearly undeployable, hard to sustain
2. AAN Army Research tank: ~7–10 T, ~4.3 mpg, claimed to offer similar protection and lethality
3. HyperVee ultralight tactical/scout vehicle, ~0.9 T
   - ~100 mpg, ultralow sustainment/signatures/profile
   - Uses very little fuel, makes 2.5 gal water/100 mi
   - Fast, agile, occupant-liftable, field-refuelable
   - 2 soldiers could load ~20 weaponized units into one C-130
   - Resists only small arms, so protected more by tactics (UAV recon)
   - Potentially formidable: in a 1982 desert experiment, Baja dune-buggies w/PGMs had a 9:1 exchange ratio against Abrams tanks (w/poor tactics), and dirtbikes w/PGMs reportedly did even better



4. Warrior in bouncy exoskeleton, ~0.09 T, 3 MRE/day
   - Might run all day @ 20–30 mph w/100-lb pack?

Naval opportunities include…

- Operational benefits to Naval Aviation: *e.g.*, from IHPTEP engines, for tactical fighter (combat air patrol) 36% lower TOGW or 44% lower fuel burn @ constant mission; ASW helos, +430% radius @ constant payload & loiter, or +80% payload @ constant radius & loiter
- Longer range/time on station? virtual ships? + lower signatures, more battle damage resistance, less maintenance and logistics burden
- Vast additional potential — subsystem to platform level
  - Just optimized fluid-handling & HVAC design is a gold-mine
  - Civilian aircraft have major scope for saving *electricity*, hence fuel
  - A recent Naval design would go faster/farther with 3 engines than 4
  - Potential Hyperships? (exploiting analogies with Hypercar® design)

Hyperships?

- Start the "design spiral" by knowing the full value of saving a ton, a m^3, and a kW in combat systems
  - *E.g.*, *direct* generating cost alone on CG-59 is worth ~$20PV/W, *excluding* all potential to decompound volume and mass
  - Mass compounding/decompounding alone is often ~5–10× in surface ships (how much depends on location and other factors)
  - Probably >>$20PV/W when m^3 and kW are decompounded too
  - We design the whole platform around the combat systems
  - But we're not optimizing those combat systems now, because nobody has determined the whole-system value of doing so
- Highly integrative design, optimizing the whole ship (and associated systems) for multiple benefits
- Ultralight, paintless, advanced-composite structures
- Advanced electric propulsion, fuel cells?, super-efficient lighting/HVAC/fluid-handling,…

An illustrative opportunity: Naval "hotel loads"

- Improve operations and equipment aboard ships, as explored in RMI's 6/01 ONR report for SECNAV
- Preliminary survey of hotel loads on typical surface combatant; NAVSEA informally concurs; next?…
- Navy uses ~$2.5b/y fuel, $0.9b to deliver it aboard
- Hotel loads use nearly one-third of the Navy's non-aviation fuel
- RMI found nearly $1M/y potential hotel load savings on Aegis cruiser *Princeton* (CG-59) — in the top quartile of class efficiency
- Electricity aboard directly costs ~$0.27/kWh to make, six times the typical industrial price ashore

Onboard "negawatts" are especially lucrative

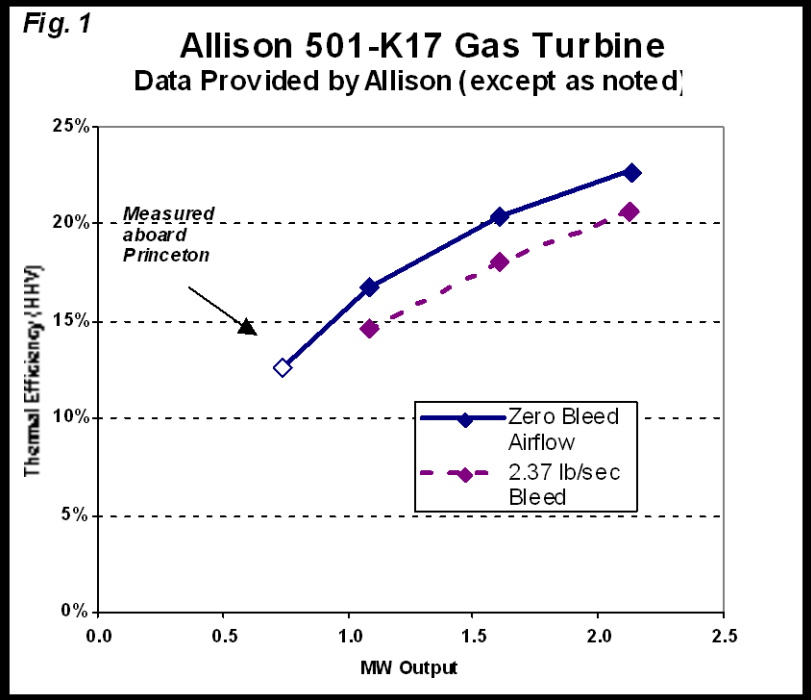
- 20-y present value of saving 1 W is nearly $20
- Making an always-on 100-hp motor one percentage point more efficient saves $1k/y
- Each chiller can save its own capital cost's worth of electricity ($120k) in eight months' operation
- Shifting two always-on fire pumps to off/pressurized/autostart mode can save $200k/y if prudent under noncritical, low-threat conditions
- $200k/y more could be saved by similar operational changes to other always-on systems
- Implies saving ~$10M present value/hull while *improving* warfighting (range, signatures,…)
- These savings could be significantly understated

CG-59's electricity costs ~$2–3M/y; ~$1M/y looks savable by retrofit

- Total CG-59 fuel use costs nearly $6M/y
- Main finding: ~20–50% of electricity could be saved by retrofitting motors, pumps, fans, chillers, lights, and potable water systems (but *none* of the radars, weapons systems, propulsion, etc.)
- NAVSEA estimated ~11% potential savings in these hotel-load systems, *plus* 8% more in propulsion, power, and combat/command
- RMI's el. savings equal up to ~10–25% of fuel
- That might reach 50–75% if combined with better electric generation and propulsion systems
- But 3/4 of el. savs. are lost unless GT ops. change

Gotcha…

Even large electrical savings will save little fuel unless GTG operational practice is also changed, because current practice runs GTGs at a low load, and still lower loads would even further worsen their efficiency; try virtual trailshafting?



Saving 1 unit of electricity from the GTG *should* save ~6–7 units of fuel, but won't, because each 2.5-MW GTG is run at ~1 MW…so saving 20–50% of electricity will save only 5–12% of GTG fuel, losing ~3/4 of savings

New-ship opportunities

- Design mentality implicit in CG-59 needs a tuneup — will we get it right in DD(X)?
  - Whole-system optimization for multiple benefits normally cuts capital as well as operating costs
  - Crucial in all-electric ships: value of a saved W?
  - Analogy of undervaluing saved amps in car design by counting only alternator sizing
  - Integrated design should work better, cost *less*
- Ultralight, ultra-low-drag analog to Hypercar?
- Innovative propulsion, power, control systems
- Low-friction design in fluid handling (10–50× savs.)
- Completely different HVAC and lighting design

RMI's 6/01 recommendations to ONR

- Rigorously scrutinize RMI's findings; if broadly correct, implement decisively fleetwide
- Accelerate NAVSEA Encon execution too
- Expand NAVSEA's physical measurements
- Resolve the longstanding single-GTG issue
- Test RMI's off+autostart, VSD, and other recommended modifications of ops practice
- Improve design philosophy, pedagogy, and practice
- Consider an intensive experiment on redesign of two vessels (1 retrofit, 1 new ["Hypership"?])
- Consider indoctrinating designers in whole-systems thinking (as RMI helped NAVFAC do w/buildings to save cap+op cost & improve quality of Service life)
- Please give RMI your feedback

Implications for all Services

- What would ultralight tactical vehicles mean for the Naval and Air Force assets needed to deploy and sustain them? Easier Sea Basing?
- How much tail-to-tooth redeployment could result from radical energy efficiency throughout land, sea, and air platforms…if DoD required it?
- How can we reward the results we want?
- How can stovepiped design culture and process be changed to optimize whole systems for multiple benefits, not components for single benefits?
- How can we purge tradeoffs, diminishing returns, and incrementalism from our design mentality?

Thank you

With gratitude to the Naval leaders who made this work possible, notably SECNAV Richard Danzig, ADM Joe Lopez (Ret.), VADM Dennis McGinn (Ret.), VADM Richard Truly (Ret.), and RADM Jay Cohen — fine teachers of the crucial difference between leadership and management.

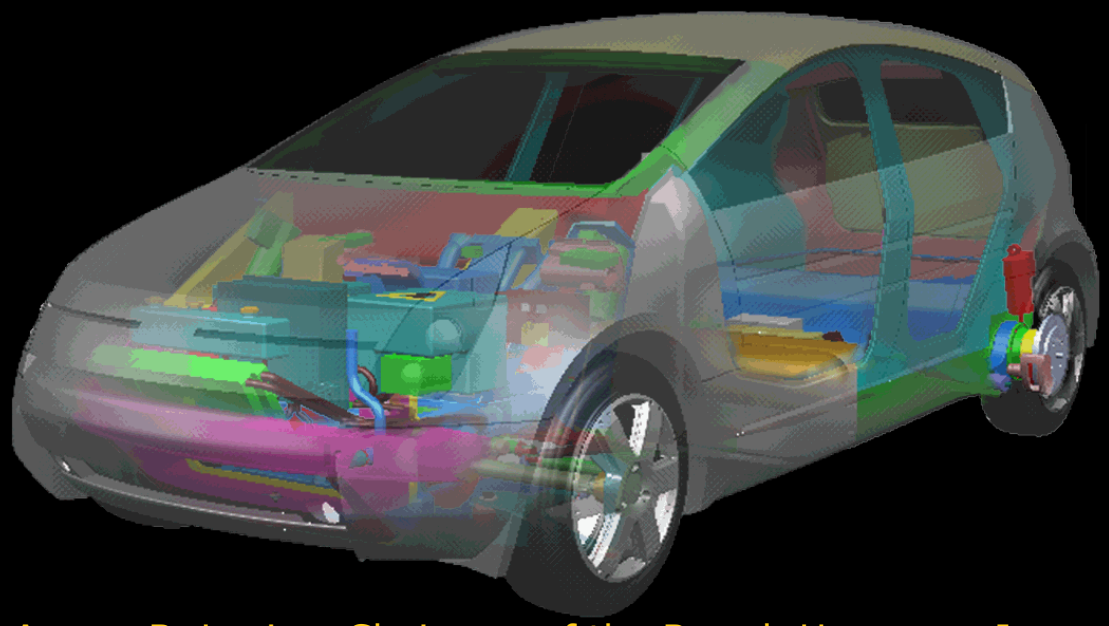
www.rmi.org

You are cordially invited to the 1615–1730 breakout session on Hypercar's unique *Revolution* concept vehicle and its H_2 fueling.

CNO's Naval-Industry R&D Partnership Conference 2003

Ronald Reagan Building, Washington, DC, 5 August 2003

How to Make 'em *Really* Better, Faster, Cheaper: Hypercar® as a Model for Integrative Design Process

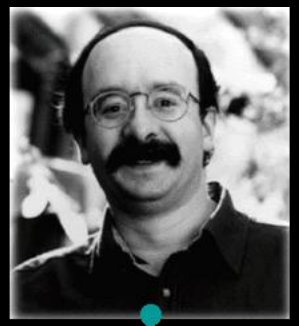


Amory B. Lovins, Chairman of the Board, Hypercar, Inc.
and CEO, Rocky Mountain Institute
www.rmi.org, www.hypercar.com, ablovins@rmi.org

Hypercar, Inc.: 12 years of **vision**

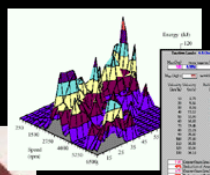
1999 Nissan Prize

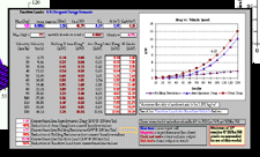
1999 & 2003 World Technology Awards

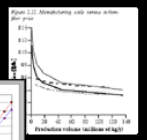


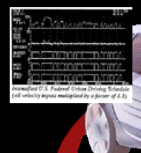
1990 — 1995 — 2000

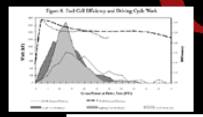
Rocky Mountain Institute → Hypercar Center → Hypercar, Inc.

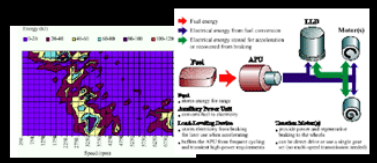


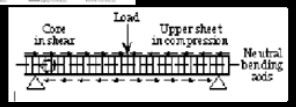




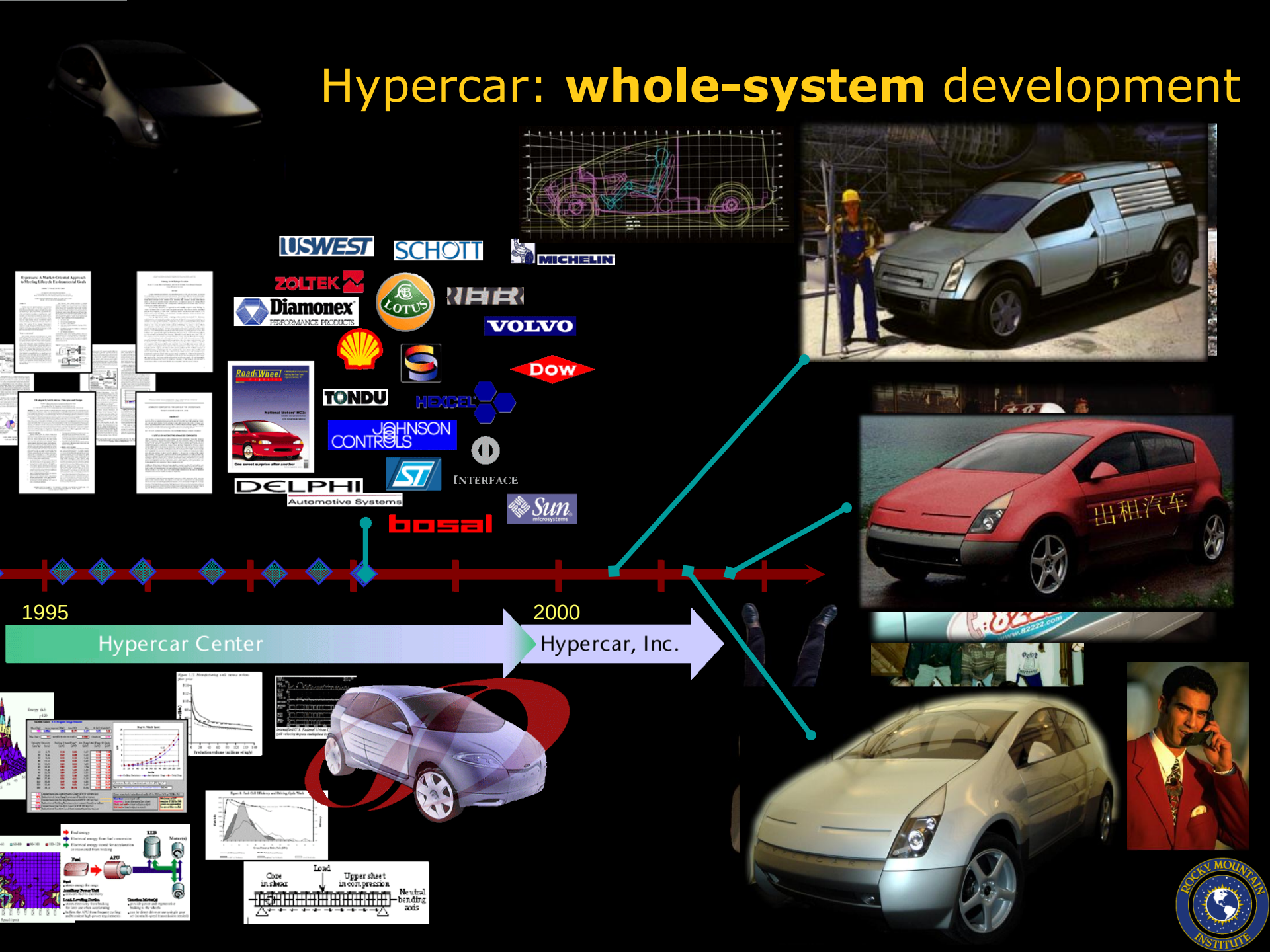








Hypercar: **whole-system** development



Show car and a complete virtual design, production-costed and manufacturable

So what about a HyperVee — a *really* lean green machine?

Can Hypercar, Inc.-like thinking yield a transformational ultralight expeditionary tactical land vehicle — *e.g.*, for Special Forces and Marines?

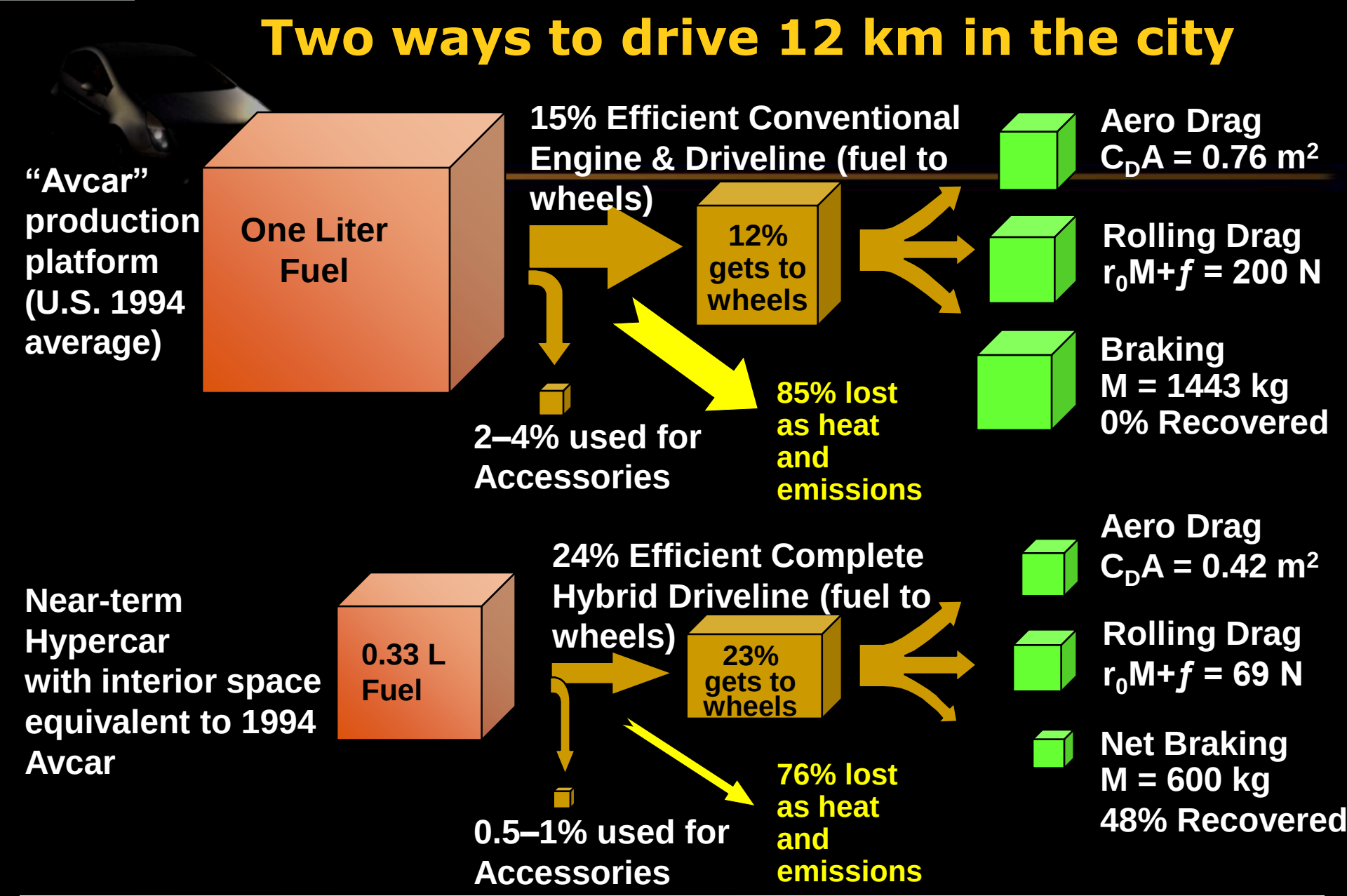
Tactical design considerations for a HyperVee

- For the mission set, what characteristics (airdrop-pability, amphibious capability, radar stealth,…) are most important and most compatible/synergistic?
- Such basic advantages as near-zero signatures, agility, low sustainment, low profile, obliquity, and small-arms protection are built-in at no extra mass or cost; carbon body could have significant fragment resistance; could Velcro on more armor (ceramics…)
- Could be an ultralight but rugged "utility vehicle": standard platform + plug-and-play mission modules
- Could change operations for other platforms, *e.g.* by providing power to serve as APU for idling tanks
- Seek most generic/complementary attribute set

Civilian Hypercar® design: six kô-an ( )

- Big fuel savings cost less than small fuel savings.
- To leap forward, think backwards.
- By not saving fuel, more fuel is saved.
- To make cars inexpensive, use costly materials.
- To make cars safer, make them much lighter.
- To get the cleanest and most efficient cars, don’t mandate them.

Two ways to drive 12 km in the city

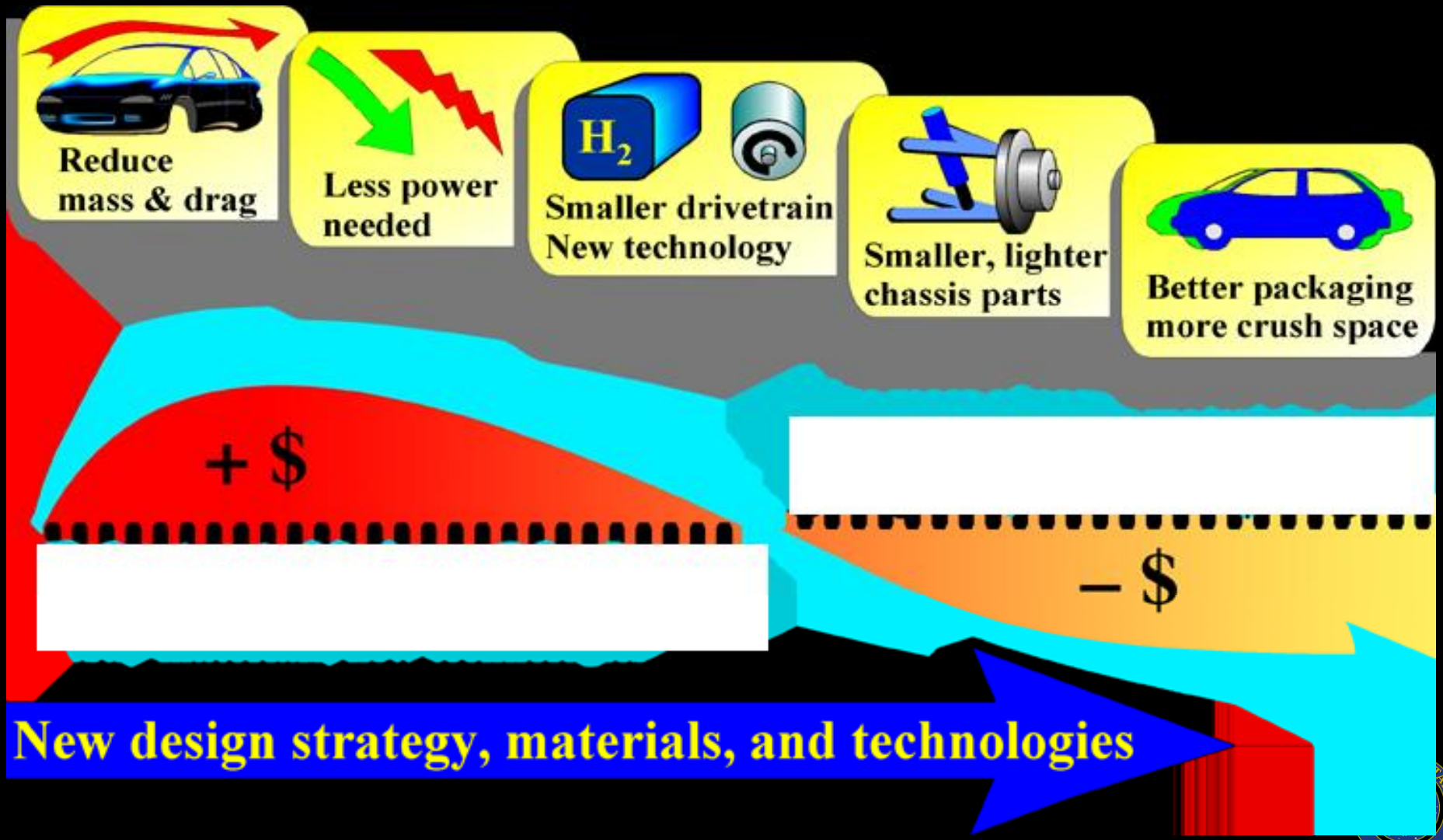


In highway driving, efficiency *falls* because there is far more irrecoverable loss to air drag (which rises as v^3) and less recoverable loss to braking.

Saving >80% of fuel…incidentally

- Conventional design: save fuel as specific goal
- Trade off and compromise other design goals (size, cost, performance, perhaps safety)
- Rely on government intervention—efficiency standards, gasoline taxes, subsidies, mandates—to induce people to buy those less attractive cars
- Hypercar design: make the car *superior*, yet comparably priced, so people will want to buy it (like buying digital media instead of vinyl phonograph records)
- This also happens to save even more fuel
- Ultralight, ultra-low-drag triggers a long series of "virtuous circles"; then hybrid drive can make the car lighter, simpler, cheaper
- Mass savings snowball… nonlinearly

Decompounding mass and com–plexity also decompounds cost



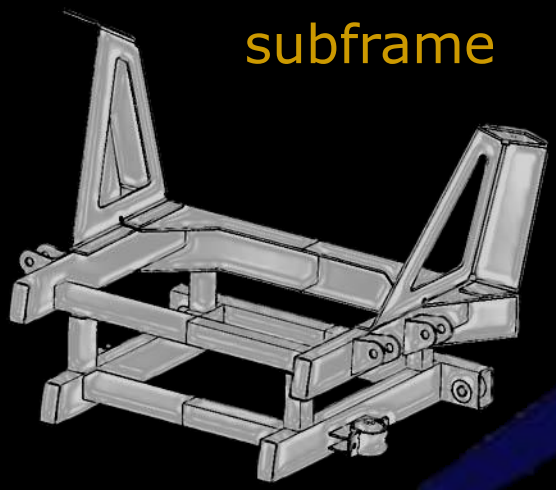
Affordable cars via costly materials

- Conventional design: stamped/welded steel
- Cheap material/kg, but costly to manufacture
- Two years to design & make ~1,000 steel dies
- High capital intensity, breakeven volume, and financial risk per model
- Long product cycle time increases risk
- Uninviting risk/reward profile

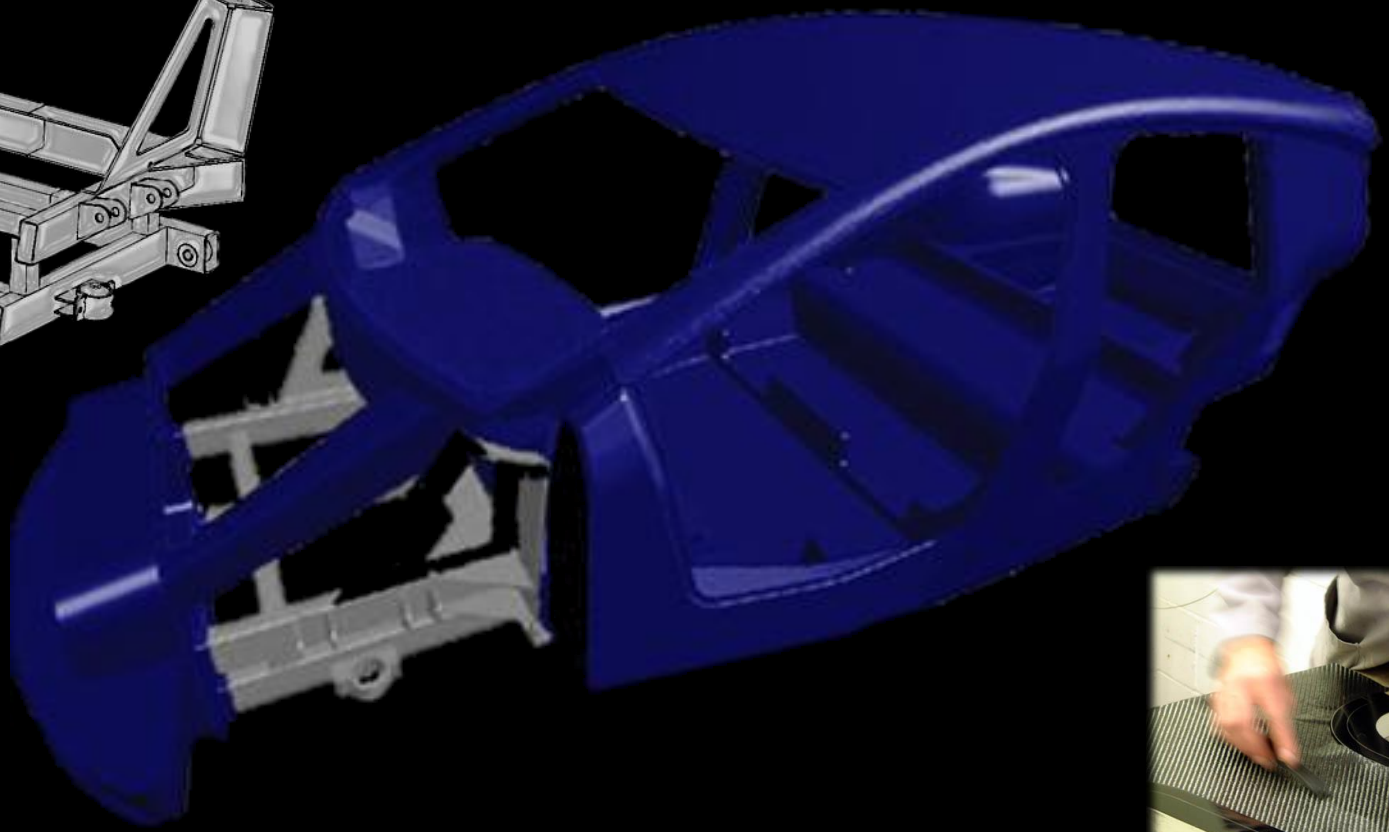
- Hypercar design: molded/ glued advanced composites
- Costly material/kg, but we all buy cars by the car, not by the kg; offset by mfg.
- <20 dies, can be soft tooling
- Self-fixturing assembly
- Many-fold less capital, assembly, parts, ?time
- Small propulsion system
- Very low breakeven volume and risk per model
- Not sumo but aikido

Ultralight autobody materials

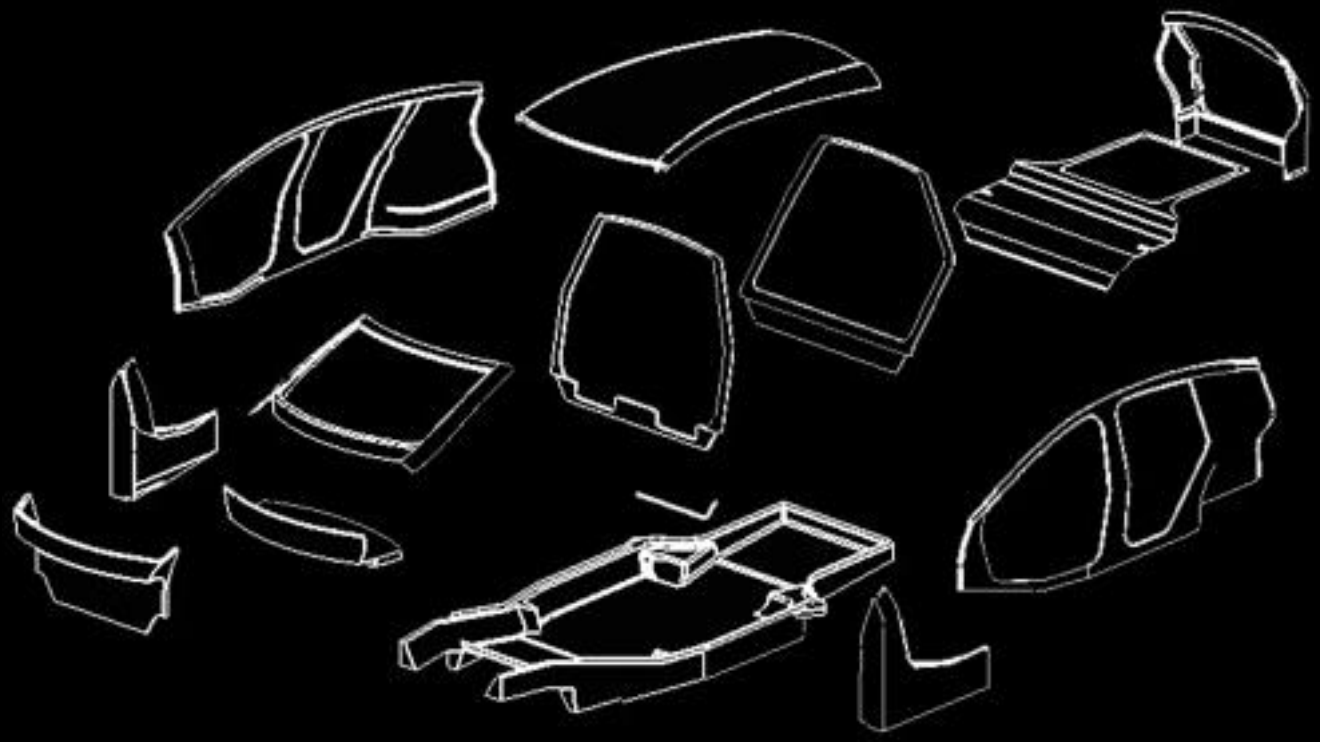
aluminum front subframe



advanced-composite passenger safety cell

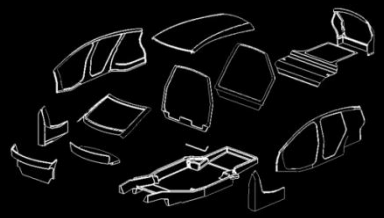


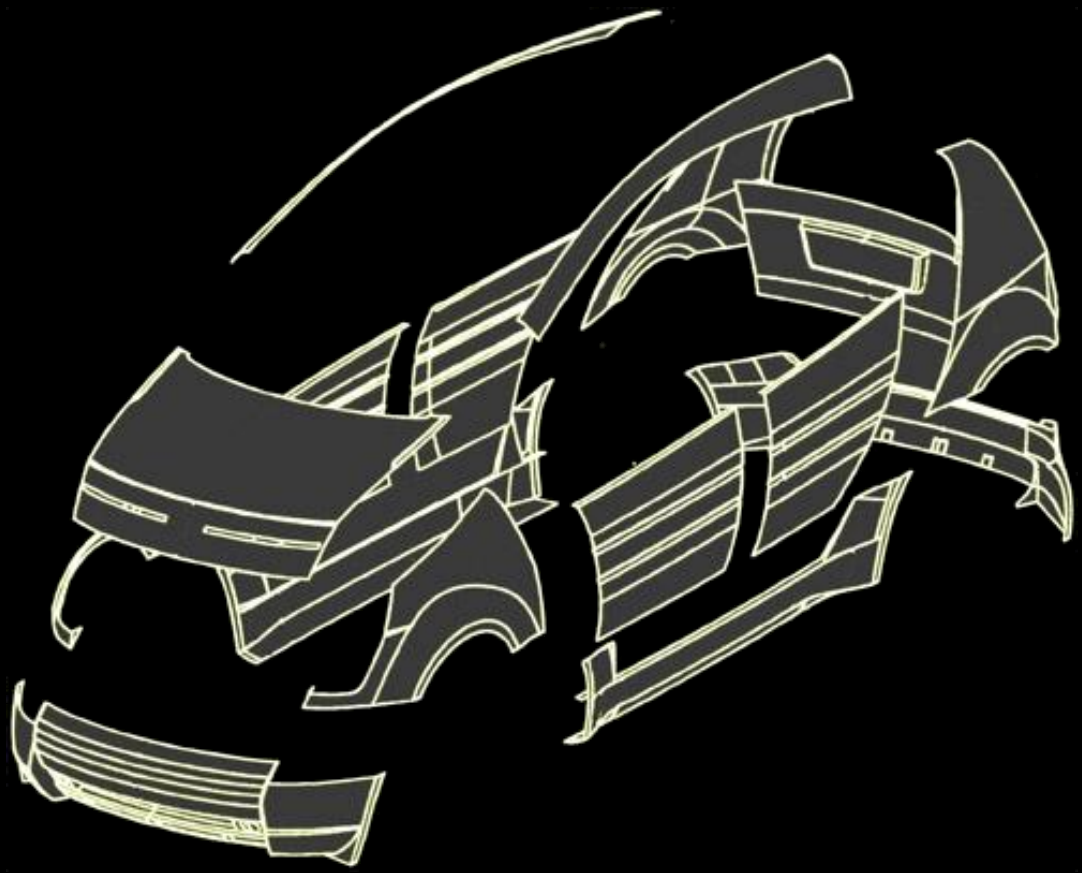
Lightweighting the **structure**



Lightweighting the **structure**

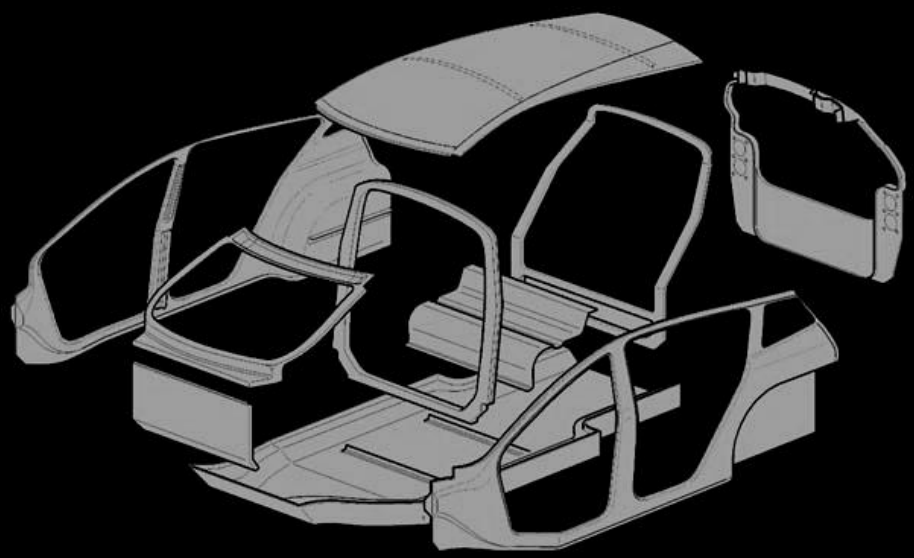
body panels

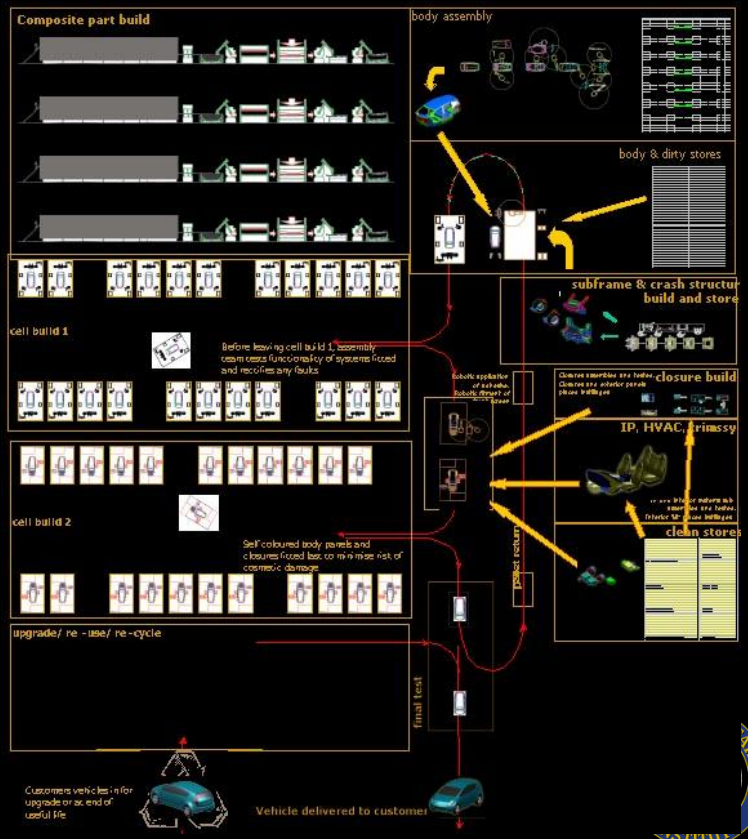




Radically simplified manufacturing

- Mass customization
  - *Revolution* designed for 50k/year production volume
  - Integration, modular design, and low-cost assembly
  - Low tooling and equipment cost

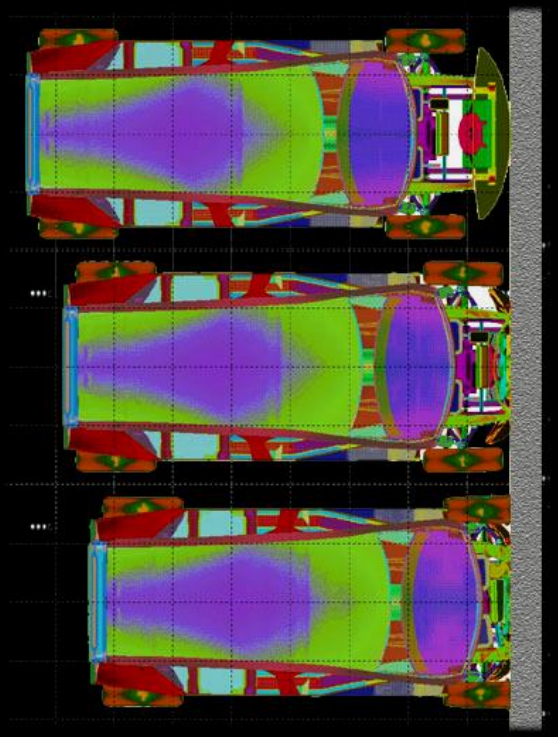


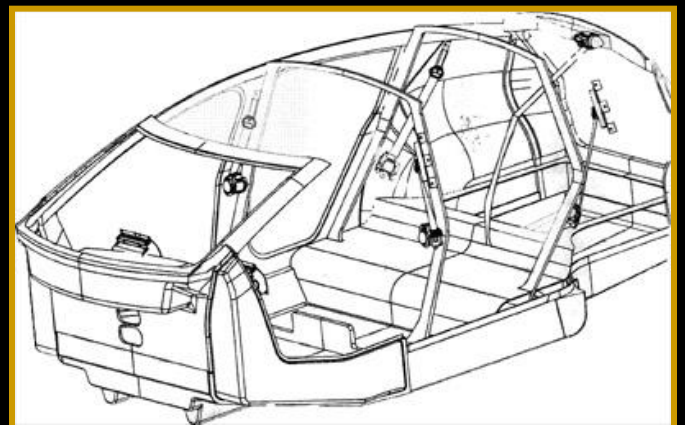


14 major structural parts, no hoists
No body shop, optional paint shop

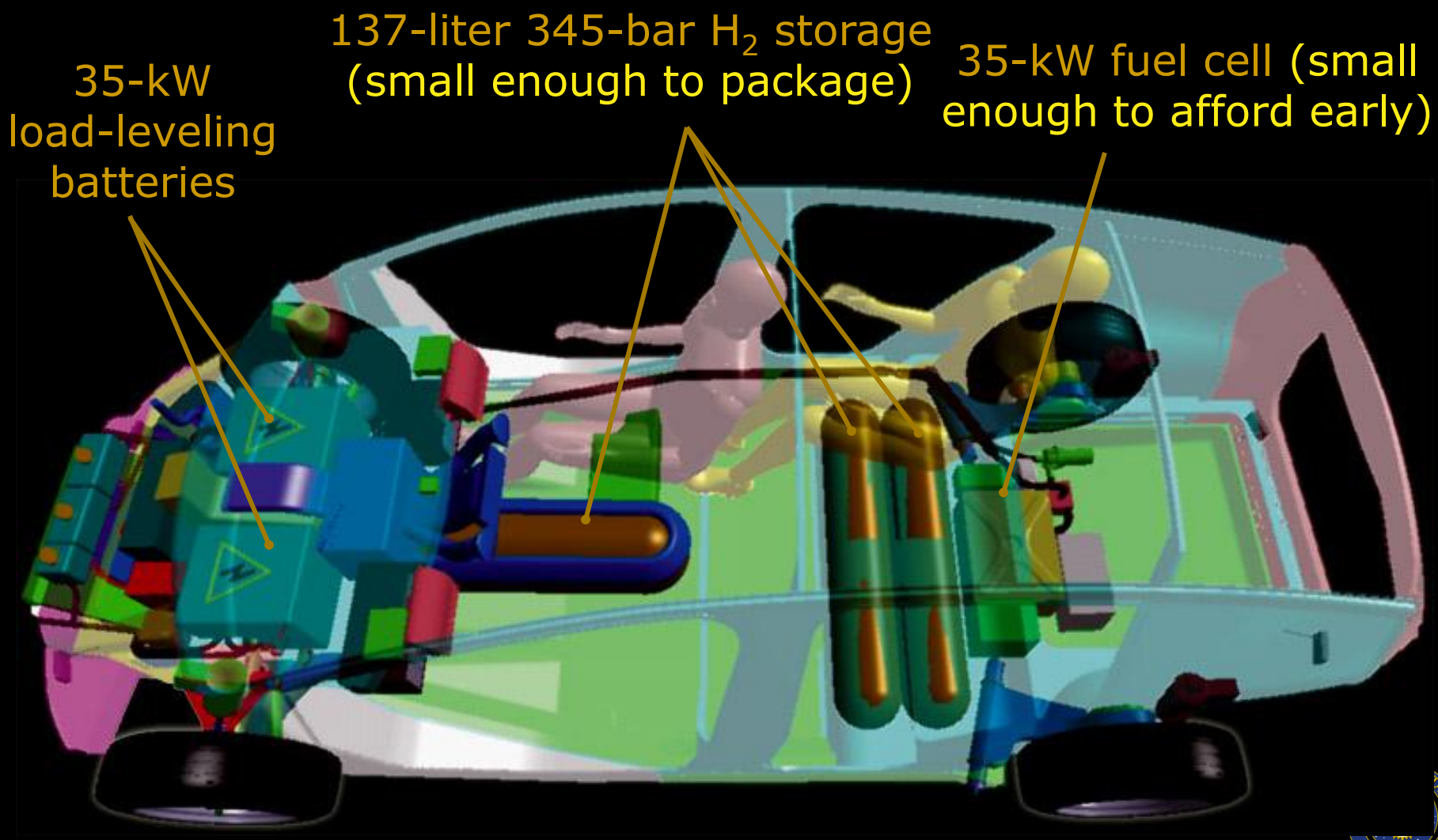
Ultralight for crashworthiness

- Carbon composites can absorb 5× as much crash energy per kg as steel (110 kJ/kg), and can do so far more smoothly
- Holistic safety design
- 10 km/h crash: no damage to autobody
- 56 km/h: no damage to passenger cell
- Head-on collision with a vehicle twice its mass, each going 48 km/h, still protects occupants from serious injury





89 km/h on same power as normal a/c, so well suited to direct-hydrogen fuel cells—enabling a rapid, profitable H_2 transition



lightweighting **pays**



Vehicle	Power (kW)	Type	Cost @ $100/kW	Range (km)
Hypercar *Revolution*	35	hybrid	**$3,500**	531
Jeep *Commander 2*	50	hybrid	**$ 5,000**	190
Hyundai *Santa Fe FCV*	75	fuel cell	**$ 7,500**	402
Honda *FCX-V4*	85	fuel cell	**$ 8,500**	298
Ford *Focus FCV*	85	hybrid	**$ 8,500**	322
Toyota *FCHV-4*	90	hybrid	**$ 9,000**	249
GM *HydroGen III*	94	fuel cell	**$ 9,400**	402
GM Hy-Wire	94	fuel cell	**$ 9,400**	129


Rapid, profitable **H_2 transition**
(RMI, NHA paper, April 1999, www.rmi.org)

- Put fuel cells first in buildings for co-/trigen + UPS
  - Fuel with natural-gas reformers (or off-peak electrolyzers)
  - Big market — buildings use 2/3 of U.S. electricity
- Meanwhile introduce H_2-ready Hypercars
  - Fleets (return nightly to the depot for refueling)
  - General market: start with customers who work in or near the buildings that by then have fuel cells
    - Use buildings' hydrogen appliances for refueling
      - Sized for peak building loads that seldom occur
    - Sell kWh and ancillary services to grid when parked
      - Marginal investment in H_2 compression/fueling, grid connection, & more durable fuel-cell stack is modest
    - Earn back much/most of cost of car ownership
      - U.S. full-fleet potential ~5–10 TW, ~6–12× grid cap.

Rapid, profitable H_2 transition (2)

- Meanwhile, hydrogen appliances get cheaper, so put them outside buildings too
  - At filling stations — a much better business than gasoline
    - Use two ubiquitous, competitive retail commodities — CH_4 and el. — and play them off against each other
    - Use just the offpeak distribution capacity for gas and electricity that is already built and paid for
    - Mainly reformers: electrolyzers are favored only at high volume, small unit scale, and cheap offpeak kWh
    - ~10^3 units @ US$6/MBTU gas beat $0.9/gal in $/mi
  - Scaleable, modular, big economies of mass-production
  - As both hydrogen and direct-hydrogen fuel-cell vehicles become widespread, bulk production and central distribution of hydrogen becomes practical and may be justified

Rapid, profitable H_2 transition (3)

- ≥2 proven, cost-effective, climate-safe methods
  - Reform natural gas at the wellhead and reinject the CO_2
    - Reforming (~8% of U.S. gas now) & reinjection are mature
    - Potentially three profit streams: H_2, $+CH_x$, $-C$
    - Strong industry interest (BP, Shell, Statoil), 200-y resource
  - Electrolyze with climate-safe electricity
    - Greatly improves ecs. of renewable electricity, bec. H_2-to-wheels is ~2–3× more efficient than gasoline-to-wheels
      - Even U.S. gasoline ($1.25/gallon) is equivalent at the wheels to $0.09–0.14/kWh electricity with a proton attached to each electron — so run dams in "Hydro-Gen" mode, shipping compressed hydrogen instead of kWh (a value-added product instead of the electron commodity)
      - H_2 storage makes wind/PV power firm and dispatchable
- Probably more: coal, oil, various renewables,...

Hydrogen-ready cars + integrated with buildings = hydrogen transition

- No technological breakthroughs required *(e.g.*, onboard reformers) — just durable and cheaper fuel cells
- Can market fuel-cell cars as soon as durable fuel cells become available, and can do so profitably many years earlier than inefficient vehicles would allow
- Meanwhile, engine or engine-hybrid Hypercar vehicles would impress (*e.g.*, ~3–3.5 L/100 km for a midsize SUV)
- No need for new liquid-fuel infrastructure (methanol, ultrapure gasoline,…) nor for liquid hydrogen
- Integrating mobile and stationary deployment makes the transition profitable at each step (>10%/y real return)
- It doesn't matter whether durable stacks come first (favoring buildings) or cheap stacks (favoring cars); whichever comes first accelerates both markets

More profitable for hydrocarbon owners too? Just try this quiz…

- (H – C) > (H + C)?
- Is the hydrogen worth more without the carbon than with the carbon?
- Is hydrogen plus negacarbon (which someone may pay you *not* to put into the air) worth more than hydrocarbon — even if carbon is worth zero?
- Is a hydrocarbon worth more feeding a refinery or a reformer?
- Should refineries become merchant H_2 plants?

(Left as an exercise for the reader. Then run, do not walk, to the hydrogen economy.)

More hydrogen surprises

- GM thinks U.S. use of natural gas would be *lower* with a miniature-gas-reformer H_2 transition, because gas used to make H_2 would be more than offset by gas saved in power plants, in boilers and furnaces, and in making H_2 for gasoline
- Sandy Thomas (www.h2gen.com) argues that global capital investment in a gas-based H_2 hydrogen fueling infrastructure over the next 40 y would be ~$1 trillion *less* than for gasoline
  - Upstream investments in gas are only ~2/3 as capital-intensive as those in oil, paying for H_2 reforming/delivery with a surplus of ~$600 per fuel-cell car served
  - Converting a filling station to make H_2 costs ~10% as much as building the station, or ~$2^1/_2$% as much as building it and its upstream fuel supply; converting 10–20% costs ~$2–4b
  - Deutsche Shell could convert all German stations in ~2 y

Good economics too

- Ford, Accenture, and many others have found that hydrogen made at filling stations or in buildings from natural gas, even at higher long-run prices (say, $6/MBTU), would compete handily with $1.30/gallon gasoline
- In round numbers, fuel cost would drop from 5¢/mile to ~3¢/mile
- The car could cost the same to buy as today's cars around (probably) the end of this decade, but would also offer many valuable advantages, plus the plug-in-power-plant option
- Carbon sequestration — centralized or not — would have a very minor effect on cost per mile

Much of the needed hydrogen is already being made for other uses

- Today's 50 MT/y H_2 (~37–45% used by refineries) — *if* it all directly fueled 5η* light vehicles instead — could displace two-thirds of all U.S. gasoline (or all by ~2010 at recent 6%/y H_2 growth)

  *Hypercar®-class platform physics mean nominally "3η" if Otto, "4η" hybrid or Diesel, "5η" (at least) if fuel-cell

- If fueling 5η light and 2η heavy vehicles, 50 MT/y H_2 could displace all U.S. highway-vehicle fuel
- U.S. refineries use ~7 MT/y H_2 — enough, if so used, to displace 1/4 of U.S. gasoline (2× Gulf share) or 1/7 of U.S. highway-vehicle fuel
- 50 MT/y H_2 could be made by ND+SD windpower
  - Byproduct O_2 could gasify biomass or coal into more H_2 or el.

Hydrogen safety

- All fuels are hazardous, but…
- Hydrogen is comparably or less so, but different
  - Buoyant (8× CH_4), diffusive (4× CH_4, 12× gasoline)
  - Clear flame can't sear you at a distance; no smoke
  - Hard to make explode; can't explode in free air; burns first
  - 4× gasoline-fume concentration required to burn; 22× less explosive power
  - Rises, doesn't puddle
  - *Hindenburg* myth (1937) — *nobody* was killed by hydrogen fire
  - Completely unrelated to hydrogen bombs

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Demonstrating hydrogen *vs.* gasoline safety

Worst-case test of deliberate H_2 leakage (L: 1.54 kg = entire tank volume in ~100 s, 185 MJ) *vs.* a 60%-lower-energy gasoline leak (R: 1.6-mm hole, 2.37 L = 0.63 USgal, 74 MJ). The H_2 flame is visible because of sodium in natural particulates in the air. This test assumed a leak at the tank's Pressure Relief Device (yielding the fastest possible loss) *and* failure of the standard H_2 sensor, pressure-drop, and flow-comparator shutoff devices. A H_2 leak *under* a fuel-cell vehicle designed to standard protocols would require failure of those 3 safety devices and of the fuel line. The H_2 and gasoline tests were done *in the same car.*

M.R. Swain, "Fuel Leak Simulation," www.eren.doe.gov, 2002.

3 s: Ignition. H_2 @ 28 L/min, gasoline @ 0.68 L/min

60 s: H_2 flow subsiding; max 47˚C on rear window, 19.4˚C on tray behind rear seat. Zooming in on gasoline car…

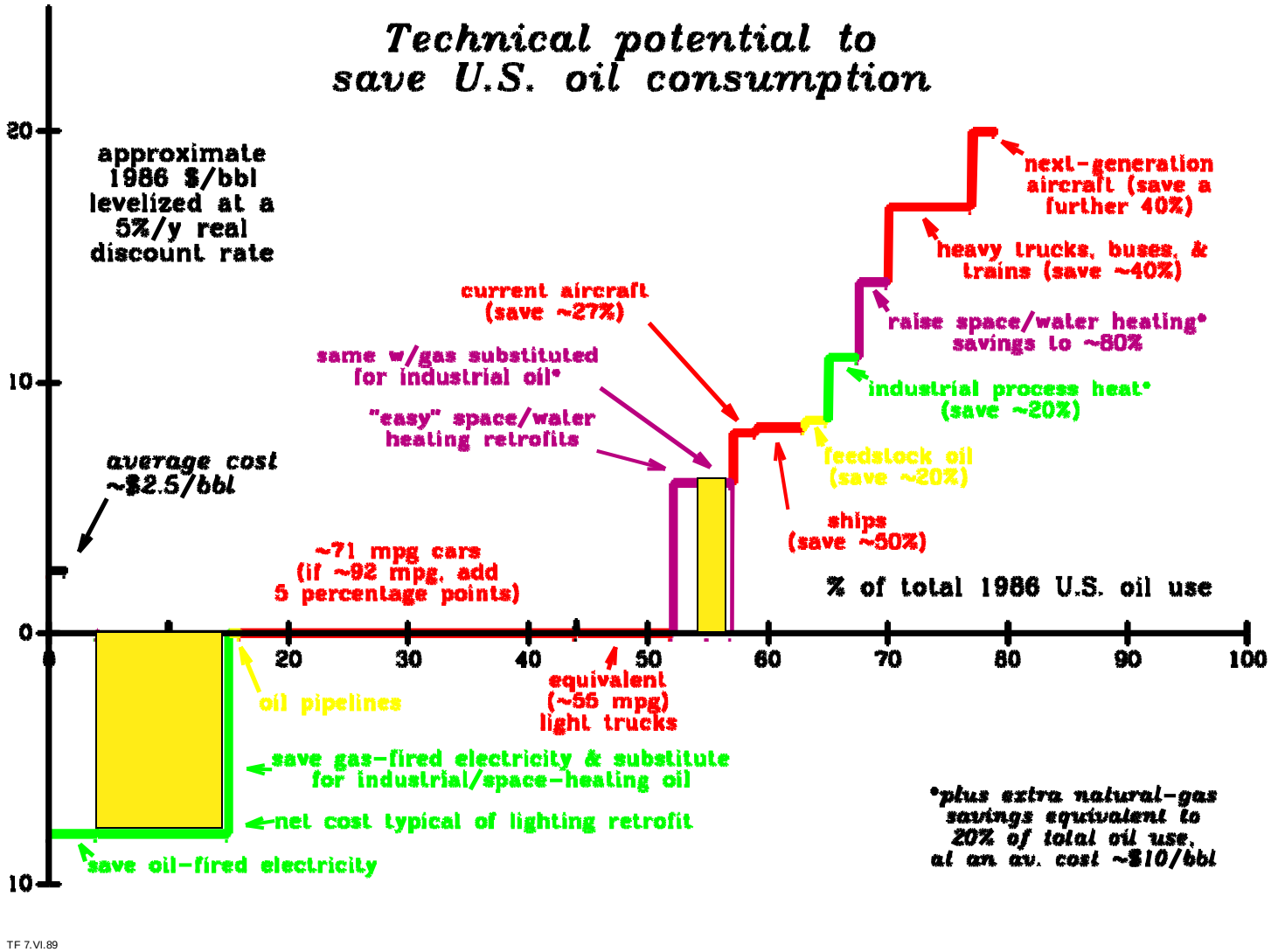
90 s: H_2 plume nearly stopped.

140 s: Gasoline-car interior alight. Tires later burst.

Hydrogen logistics

- Generally safer than liquid hydrocarbon fuels
  - Ultrastrong carbon tank is extremely resistant to battle damage; cushioned H_2-filled tanks could readily be airdropped & plugged in
  - ~14× less mass of fuel onboard per unit range
- Feasible (though awkward) to deliver in bulk
- Typically easier to produce in-theater at any scale
  - From any hydrocarbon or carbohydrate with a portable reformer
  - Or from water + electricity from any source, even idling tank/truck
  - Extensive off-the-shelf hardware is available, more on the way
- Double logistics advantage — fuel and drinking water
- Worth re-examining the single-fuel doctrine
- Or solid-oxide fuel cells: burn hydrocarbons directly

A 1987–88 RMI Analysis for Shell Found a Retrofit Potential to Save ~80% of U.S. Oil at Average Levelized Cost ~US$2½/bbl…



…but now every step is known to be bigger and cheaper!

Contingency: off-oil mobilization

- RMI synthesis is now synthesizing a full, rapid, attractive, *profitable* U.S. off-oil roadmap for business and military leaders
- This exercise, co-funded by DoD, will:
  - update, w/2 variants, RMI's 1987–88 Shell supply curve for oil end-use efficiency & saved natural gas; these could have saved 80% of 1986 oil use @ $2.5/bbl — now more & cheaper
  - add an aggressive supply-side transition (biofuels, hydrogen)
  - analyze how much of the unbought overhang of oil savings can be elicited by traditional plus ~15–20 new policy instruments (those *not* using price, tax, or de/regulation)
- Expected to be more profitable for the country and probably also for hydrocarbon companies
- Both contingency and business opportunity

The oil endgame is starting

- Many oil majors wonder whether to say so; the chairs of four already did (plus those of three big automakers)
- The China-led hydrogen/Hypercar leapfrog in Shell's 10/01 "Spirit of the Coming Age" scenario is clearly now underway, with strong support from the highest levels
- Oil will probably become uncompetitive even at low prices before it becomes unavailable even at high prices
- Don Huberts, Geoffrey Ballard, Sheikh Yamani: "The Stone Age did not end because the world ran out of stones, and the Oil Age will not end because the world runs out of oil"
- Like uranium already and coal increasingly, oil will become not worth extracting — good mainly for holding up the ground — because other ways to do the same tasks are better and cheaper

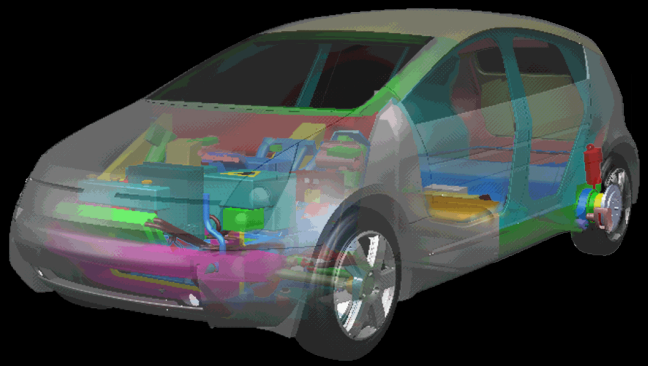
It's time — and integrative engineering can lead the way

"People and nations behave wisely —
once they have exhausted all other alternatives."
— Churchill

"Sometimes one must do what is necessary."
— Churchill

"We are the people we have been waiting for."

www.rmi.org



www.hypercar.com