



JSC-Energy Systems Division

Spacecraft Power Systems Engineering

Solutions for NASA's Manned Space Program

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My task is to provide an overview of spacecraft power systems:

- History
- State-of-the-art
- Development directions

- Focus on applications in the manned space program led from JSC
 - My expertise is manned vehicles
 - Also in direct conversion technology (batteries and fuel cells) and nuclear power generation – so I'll emphasize that



Elements of Spacecraft Power Systems



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- Power Systems Engineering Trade Space
- Power Generation and Energy Storage
- Power Distribution and Control
- Actuation

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I'll discuss:

- How basic systems engineering trades are conducted for spacecraft in a way quite different for more general applications
- Solutions chosen via this process for manned spacecraft in
 - Power generation & energy storage
 - EPD&C
 - Actuation (thrust vector and control surfaces), including electromechanical actuation



Commercial/Military Electric Power Systems:

- Development, Production & Operation Cost (\$/kW)
- Specific Power/Energy (kW/kg, kWh/kg)
- Emissions (NO_x, CO_x, noise)

Constraint: Public Safety

There are common considerations for the design of a power system for any application, with only a variation in priority.

- Cost
- Density
- Emissions

All must be optimized within an absolute constraint of safe operation in the field.



Spacecraft Electric Power Systems:

- Specific Power/Energy (kW/kg; kWh/kg)
- Specific Power/Energy (kW/kg; kWh/kg)
- Specific Power/Energy (kW/kg; kWh/kg)

Constraint: Mission Reliability

Override: Development Cost (\$MM)

For spacecraft, things are like with real estate

With launch costs hovering at \$20K/kg, specific power/energy overwhelms almost any other consideration

- NASA sticks to this rule, but has begun to sometimes run up against exceptions (which we'll discuss)

The absolute constraints is not public safety but mission reliability, almost always judged by verifiable redundancy.

TWO FAULT TOLERANT TO CATASTROPHIC FAILURE = AT LEAST THREE INDEPENDENT POWER STRINGS....as far as we can push it. Redundancy management is crucial.

PRA calculations are only a minor input to design decisions, as database is too small. PRA's are used in operational decisions.

We will push these until we hit the overriding constraint of development funding. Note that recurring production and even operational costs are not primary considerations. We don't fly enough.



Power Generation and Energy Storage



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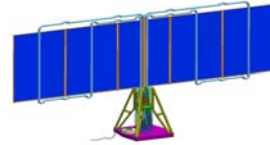
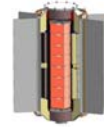


Photovoltaics



Direct Chemical
Conversion

- Batteries
- Fuel Cells



Nuclear

- Decay
- Fission

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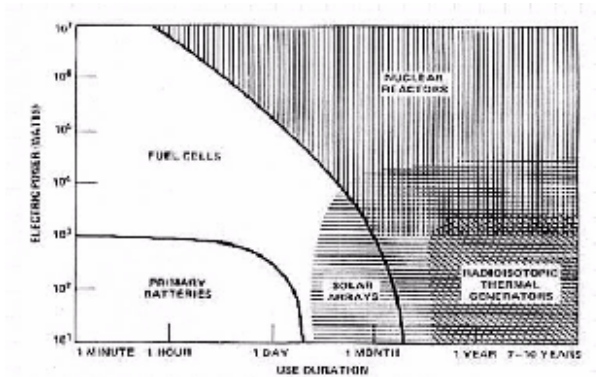
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Three categories of technologies for generation & storage

- Solar sources (photovoltaics for direct electric generation)
- Direct chemical conversion (primary batteries and fuel cells for generation only and secondary batteries and regenerative fuel cells for storage of energy from other generation sources)
- Nuclear sources (radioactive decay with Pu and atomic fission) with heat engine conversion



Primary Power Specific Energy Trade Space



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Defines minimum mass solutions for dimensions of power and mission duration.

- Very old textbook chart
- Lines have not and will not move much
- Changes are only in the development cost (from ground state-of-the-art to spaceflight-ready) and perceived development risk of each solution.



Trade Space for Electric Power Systems



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Manned Spacecraft Power System Selections

	Mercury	Gemini	Apollo	Skylab	Shuttle	ISS	X-38	CEV	Future
Primary Batteries	X						X		?
Secondary Battery Storage				X		X	X	x?	?
Primary Fuel Cells		X	X		X				?
Regenerative Fuel Cell Storage								x?	?
Photovoltaics				X		X		X	?
Nuclear									?

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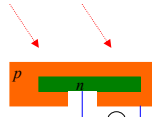
kWh needed and development cost/risk have driven solutions selected for manned spacecraft. Mercury was a short mission with low power demand. ISS has nearly indefinite mission length with high power demand. Development cost has kept nuclear power from any manned mission.



Solar Power

Photovoltaic arrays

sunlight



Silicon: $\eta < 10\%$
Gallium Arsenide: $\eta < 15\%$

Conversion efficiency improvements are focus of much research in nanotechnology



Unmanned spacecraft limited to surface-mount or one-time deployable arrays



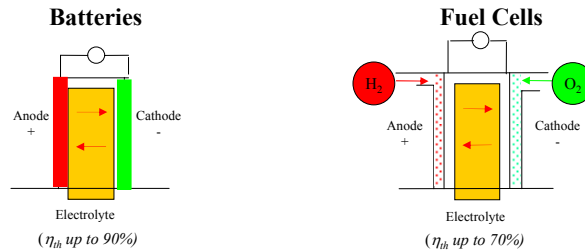
Manned spacecraft capable of deployable, pointable, and retractable arrays



- Photovoltaics produce power from the photoelectric effect: incident sunlight creates an electric potential between p and n semiconductors that can drive a current.
 - Electromagnetic conversion efficiency driven by semiconductor materials selected. Much nanotechnology research is focused improvements.
- Solar photovoltaics remain solution of choice for near earth power generation
 - First utilized in 1970s
 - Much materials research focused on improvements in very low efficiency
 - Yield linear improvement in surface area and mass
- Concerns with reliability of kinematic chains limit unmanned spacecraft to surface mount arrays or to one time deployable arrays (with accompanying limits on maneuverability)
- Availability of astronaut intervention as back-up enables much more efficient arrays on manned spacecraft with retractability available to allow energetic mission maneuvers and pointing mechanisms to optimize power levels.
 - Note that the ISS arrays' two-axis pointing and deployment/retraction abilities have been utilized three times. Two of those times have required astronaut intervention.



Direct Chemical Conversion Batteries and Fuel Cells



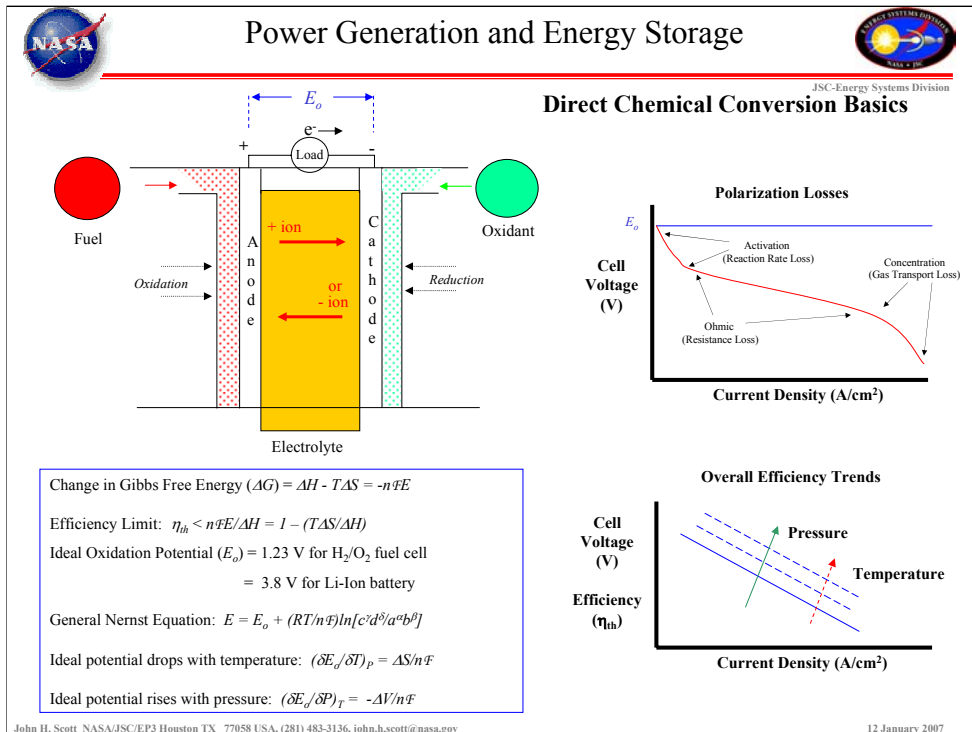
Primary Power and Secondary Storage

Batteries and fuel cells can each be used as either a primary power source or as a secondary energy storage system

- Fuel cells have fuel and oxidant fed to or generated from storage tanks
- Batteries contain all chemical reactants internally

• Both technologies have been focused on large commercial investment for industrial and transportation applications

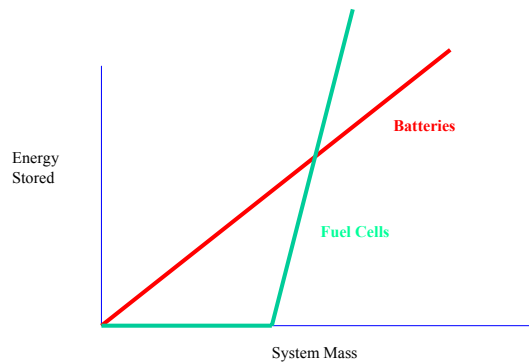
• NASA has tried to take advantage of this to meet its mission requirements...with varying degrees of success.



- In direct direct chemical conversion, a current is driven by the electrochemical potential of a fuel/oxidant pair driving ions through an electrolyte.
- Efficiency limited by ratio between Gibbs Free Energy and Enthalpy released by the reaction rather than by differences in temperature between heat addition and rejection.
- Available potential is driven by reactivity (e.g., concentration) of species involved (partial pressure in fuel cells; state of charge in batteries)
- The practical performance limitations on both batteries and fuel cells are driven by the shape of the polarization curve, which is in turn driven by reaction kinetics and cell pressure and temperature.
- Shape of polarization curve is subject of considerable engineering, especially nanotechnology
- JSC has significant participation in such work with JPL and GRC.



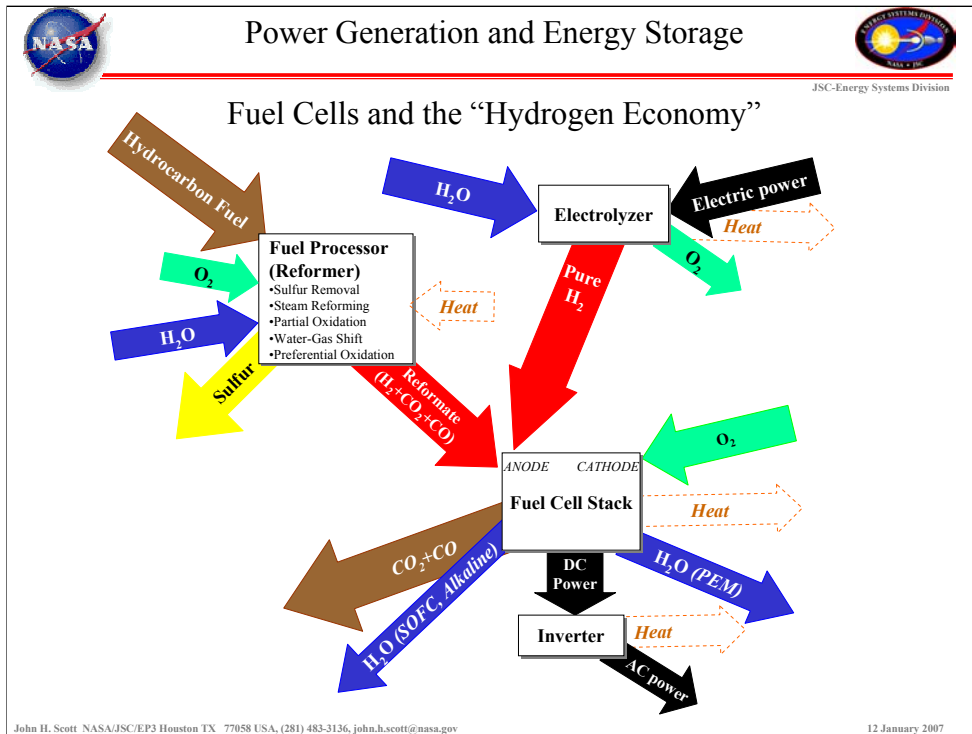
Direct Chemical Conversion Batteries and Fuel Cells



For a 10 kW spacecraft bus demand and a comparison between SOA Li-Polymer batteries and H₂/O₂ alkaline fuel cells with supercritical storage, lines cross at about 26 hrs.

Fuel cell line slope will likely not change, though dry mass by decrease by ~20%. Li-Ion battery slope (i.e. specific energy) may improve dramatically (almost double). With this, lines would cross at ~50 hrs.

The shuttle drew 13-15 kW on-orbit during the last mission.



Commercial investment in Hydrogen Economy focuses on problems very different from manned program needs.

- Minimize expensive catalyst vs. Maximize efficiency
- NASA has little concern for manufacturing cost
- Manned program needs much greater durability and highest possible thermodynamic efficiency.
- Commercial focus on fuel reforming and contaminant compatibility vs. NASA availability of pure reactants
 - May be common ground in electrolysis for producing oxygen on moon

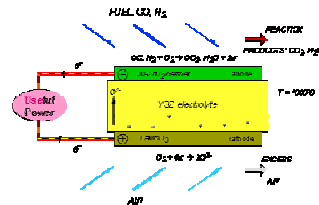


Power Generation and Energy Storage



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Spacecraft Fuel Cell Development



Alkaline

- >0.9 V/cell with pure reactants
- Operate at ~80 °C
- High rate load following
- ~5000 hr durability
- Fuel-side water management
- Best solution for manned spacecraft to date
 - Apollo
 - Shuttle
 - ISS (Electrolysis for O₂ production)

Proton Exchange Membrane

- >0.8 V/cell with pure reactants
- Operate at ~90 °C
- Compatible with CO₂
- High rate load following
- >10,000 hr durability
- Oxidant-side water management
 - Gravity independence difficult
- Focus of commercial investment
- Needed for long duration spacecraft
- Regenerative applications

Solid Oxide

- >1.0 V/cell with pure reactants
- Operate at ~800-900 °C
- Compatible with many impurities
- Very poor load following
- Unproven durability
- No water management in stack
- Possible solution for steady load applications
 - Electrolysis for lunar O₂ production

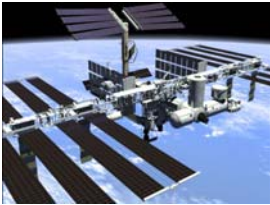
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- While fuel cells can be run on a variety of fuels and oxidants (e.g. methanol and hydrogen peroxide), the reactants of most interest both commercially and from NASA are hydrogen and oxygen.
- Fuel cells capabilities are characterized by the electrolyte chosen and the temperature at which the electrolyte is ionically conductive and durable..
- Since spacecraft to date have been able to rely on absolutely pure reactants, alkaline chemistry has provided the best solution to date for LEO manned missions of <30 days.
 - Durability, while sufficient for Apollo and Shuttle, may not meet requirements of longer missions.
 - ISS electrolysis is done with alkaline
- PEM fuel cells are somewhat less efficient but theoretically more durable than alkaline.
 - Much commercial investment is going into PEM as they can work with reformat, but two-phase water management is an issue for durability.
 - Industry focused minimizing the amount of precious metal catalyst (~0.4 mg/cm²) with at least 2000 hour durability
 - NASA testing focused on maximizing cell voltage (will accept 25 mg/cm² in catalyst) with >10,000 hour durability. Water management is also a greater challenge without gravity.
 - NASA and industry have interest in high temp (120 C) PEM.
- Solid Oxide fuel cells are very efficient but high temperature
 - Much commercial interest in APU applications (steady load), as SOFC can work with dirty fuels (even directly oxidize CO, CH₄).....SECA project.
 - Cycle life is a challenge
 - Exploration may find this useful for steady electrolysis applications.



Secondary Battery Energy Storage



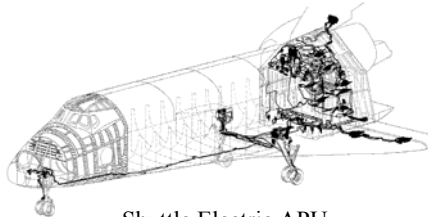
ISS



EMU



X-38



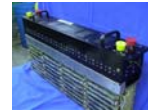
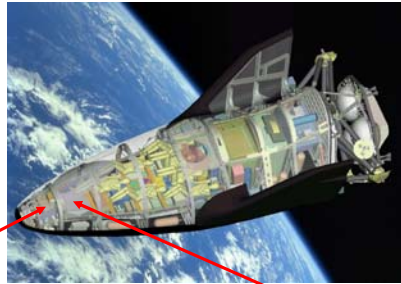
Shuttle Electric APU

- NASA requirements not much different from commercial
 - NASA has much less concern for recurring cost
 - ISS Ni-H battery is expensive
 - NASA has more extreme durability/reliability requirements
 - Good results have been obtained in applying commercially developed battery CELL technology to manned space applications.
- Four programs provide examples:
 - ISS
 - Space Shuttle Electrohydraulic pump upgrade study (not flown)
 - EMU upgrades
 - X-38 (prototype crew escape vehicle for ISS-not flown)



Secondary Battery Energy Storage

X-38 Project selected different battery chemistries per rate requirements



Ni-Cd for 260 V actuation

- Deliver 4.1 kWh; 104 kW max power
- 16 Wh/kg
- Discharge rates ramp from 1 C to 10 C
- Trickle charge maintenance
- Space vacuum environment

NiMH for 28 V housekeeping

- Deliver 10.8 kWh
- 32 Wh/kg
- C/3 steady discharge rate
- C/8 charge rate
- In-cabin environment

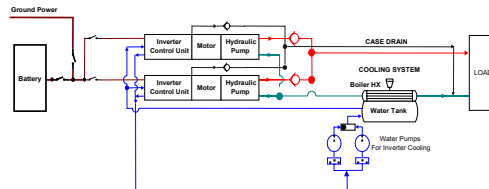
- Secondary batteries selected to allow for top off after checkouts on-orbit
- Rate capability at best specific energy drove chemistry selection.
- X-38 program developed concept of custom aerospace batteries built up from small, lot screened, commercially manufactured cells.
 - Greatly reduced development cost
 - Minor hit in specific energy



Secondary Battery Energy Storage

Shuttle “Electric APU” studied as path to relieve hazardous turnaround operations

- Weight **increase** of 2000 lbs accepted!



Li-Ion chemistry selected for mass, life, and rate ability

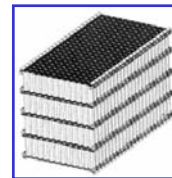
- 28kWh @ ~80 Wh/kg; 130 kW peak power
- 230-360 VDC
- Two design solutions competed on cost



“Large Cell”
82S



“Small Cell”
82S-88P



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- EAPU project developed to replace hydrazine gas turbine-driven hydraulic pumps) with battery-fed electric hydraulic pumps (33 gpm max each).
- Shuttle Program invested in EAPU development for operational hazard reduction at the price of INCREASED weight.
 - Hydrazine fueled APUs were a hazard during turnaround ops and considered high flight safety risk.
- Li-ion chosen for mass, rate, and life (rechargeable between missions)
 - Peak power at end of mission: low voltage capability in motor control (nominally 270V) traded with total battery size and thermal runaway risk.
- Technology program traded between single string of large, aerospace cells (ability to bypass failed cell) and multiple strings of small, commercial cells.
- Planned retirement of Shuttle in 2010 led to cancellation technology program after Columbia accident and before completion.



Secondary Battery Energy Storage

ISS eclipse storage batteries selected for cycle life and specific energy



Ni-H₂ in operation

- $\eta_{th} = 85\%$ BOL
- 29 W-hr/kg
- 50 W-hr/l
- 40,000 cycle life



Li-Ion replacements under study

- $\eta_{th} = 95\%$ BOL
- 70 W-hr/kg
- 250 W-hr/l
- 10,000+? cycle life

- The nickel hydrogen batteries in use for ISS eclipse energy storage were the best cycle life and energy density available in the 1980's (at any price....very expensive)
- EOL replacements may take advantage of tremendous growth in Li-Ion technology.
 - Improved round-trip efficiency (thus, less heat load)
 - Vastly improved volumetric energy density (more payload room)
 - Cycle life in question
 - Possibly cheaper to procure (use of commercially produced, standard cells)
 - Study and test program on-going



Secondary Battery Energy Storage

Extravehicular Mobility Unit (EMU) battery replacement chosen for durability.



Ag-Zn in flight operation

- $\eta_{th} = 70\%$
- 80 Wh/kg EOL
- 32 cycle life
- 15 month calendar life
- Crew activation and maintenance on-orbit



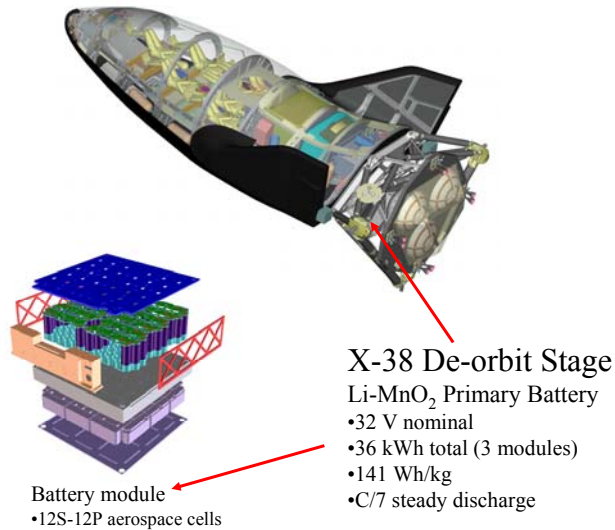
Li-Ion replacements in development

- $\eta_{th} = 90\%$
- 67 Wh/kg EOL
- 100 cycle life
- 5 year calendar life
- No crew activation or maintenance

- In order to reduce crew maintenance time and increase life, commercially developed lithium polymer cells have been selected to replace silver zinc batteries on orbit
- Specific energy is slightly sacrificed to greatly increase durability.
- Improved thermal efficiency is provided but is not a driver for the new design.



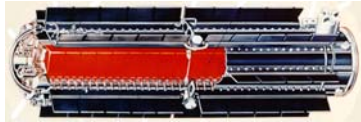
Primary Battery Energy Storage



- Primary battery chosen to maximize specific energy at rate required.
- Heat sink for adiabatic discharge to eliminate need for in-space heat rejection
 - Very high specific energy, even including heat sink
 - Relatively low discharge rate.

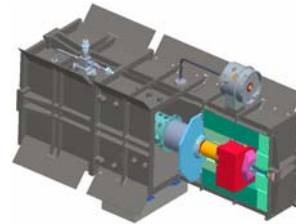


Nuclear Power Radioactive Decay



Radioisotope Thermoelectric Generation (RTG)

- Decay heat to DC electricity via thermoelectrics
- <8% conversion efficiency
- Specific power ~3/W/kg
- Long history in unmanned deep space probes



Advanced Stirling Radioisotope Generator

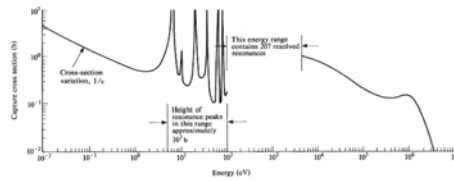
- Decay heat to AC electricity via Stirling conversion
- >30% conversion efficiency
- Specific power ~7 W/kg
- Next generation technology

Decay heat from either Pu or Po

- Raw material extremely expensive, no longer being made in the US.
- RTGs have a long and successful history in space probes
 - Apollo experiment packages, Pioneer, Voyager, Viking, Galileo, Ulysses, Cassini, New Horizons (40 to 245 We)
 - Extremely high specific energy (45 kg RTG run 14 years @ 100W = 270 kWh/kg)
 - Very low specific power
- DIPS is a new generation system yet to be flown
 - Enabled by development of small scale, balanced Stirling engines
 - Better than double the specific power.
- Exploration applications envisioned for unmanned rovers



Nuclear Power Fission Power Reactors



U-235 Neutron Capture Spectrum



SNAP-10
 • Launched 1965
 • ~500 We



SP-100
 • Designed 1990's
 • 100 kWe
 • Thermoelectric
 • Fast spectrum
 • Li coolant
 • T = 1375K
 • Nb-Zr cladding



JIMO
 • Designed 2000's
 • 200 kWe
 • Brayton
 • Fast spectrum
 • HeXe coolant
 • T = 1050K
 • Refractory cladding



Fission Surface Power
 • Current study group
 • 25-100 kWe
 • Brayton or stirling
 • Fast spectrum
 • NaK coolant
 • T = 900K
 • Stainless steel cladding

- Drive to increase specific energy leads to choice of fast spectrum reactors
 - Less moderator mass but higher U-235 fuel loading.
 - Weight savings requires more enriched uranium
- SNAP-10A (which flew!) and SP-100 program intended as demonstrators
 - High temperature thermoelectric conversion to save radiator mass (radiator area as T⁴!)
- Jupiter Icy Moons Orbiter JIMO had specific mission
 - High temperature brayton conversion to save radiator mass
- Programs to date required expensive materials development for reactor
- Surface power study aims at using current civil/navy reactor materials
 - Lower development costs trade well for increased radiator mass
 - Higher fuel enrichment adds to security cost



Power Distribution and Control



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28 VDC unregulated, redundant bus historical baseline in manned spacecraft

- Aircraft heritage
- Acceptable efficiency with low current, short cable runs, resistive loads
- Safe for crew contact
- Requires stiff source for voltage control



Shuttle Orbiter



ISS Russian Segment

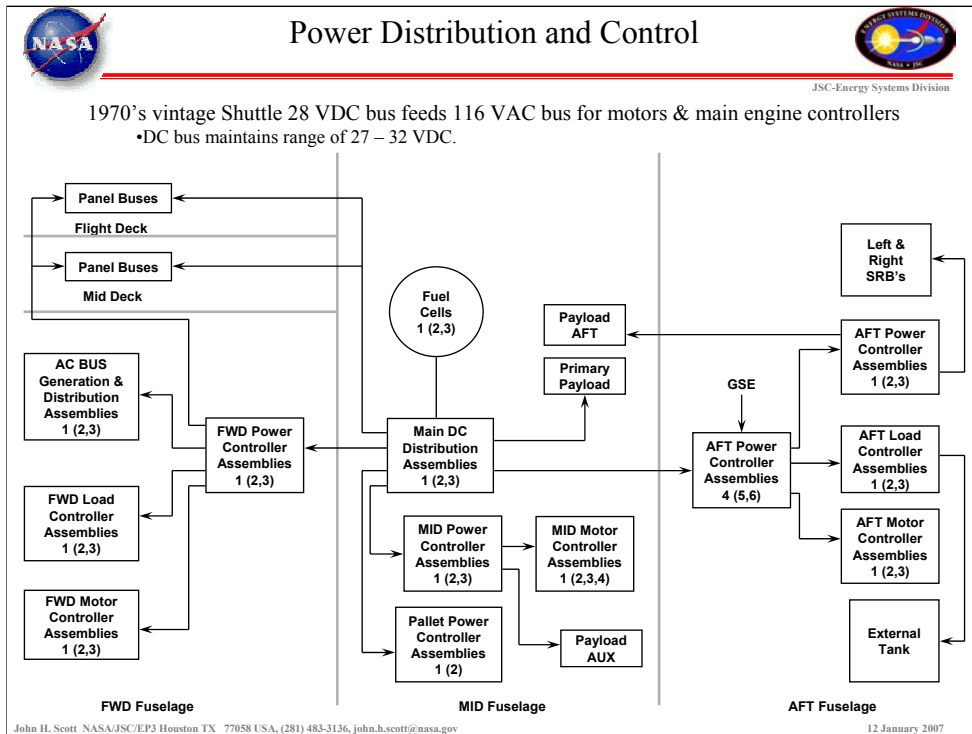


X-38

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- Aircraft-heritage 28 VDC systems have been the baseline power distribution solution for manned spacecraft (Mercury, Gemini, Apollo, Soyuz)
- Allow acceptable losses with low power (<20 kW) systems made up of primarily resistive loads
- Not a shock hazard
- Lack of active regulation requires low impedance source to maintain voltage within a reasonable range
- We'll see how such systems have been implemented on Shuttle, the X-38, and the ISS Russian Segment



- Shuttle Orbiter has three cross-strapped 28 VDC buses, each fed by a fuel cell with 12 kW nominal power. With all but the most critical equipment powered down, the Orbiter could land on one of these. Triple redundancy only really exists for the GPCs
- 28 VDC (27-32 VDC)

• As DC motors were poor options in the 1970's (permanent magnets of sufficient field were expensive, heavy, and temperature sensitive) the Shuttle was designed with 3 116 VAC, 3 phase, buses fed via inverters from the DC buses to serve motor and some computers. These busses are not cross strapped (complicated for AC), but crew can install jumpers within the cabin.

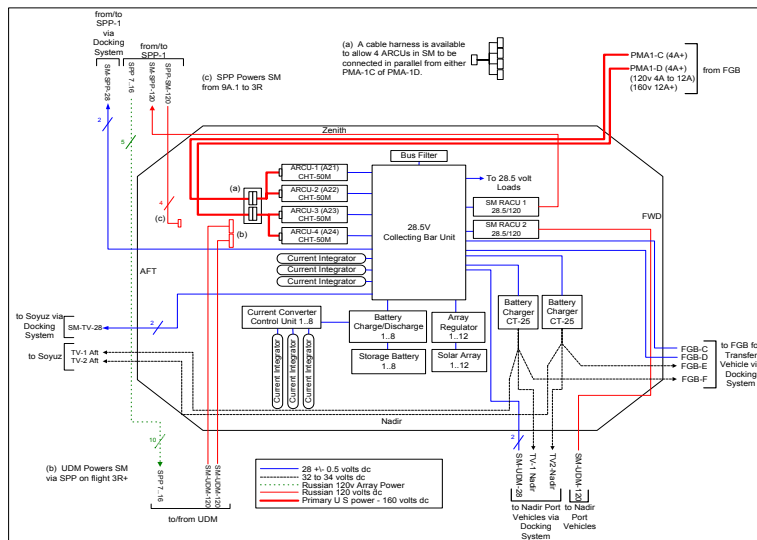


Power Distribution and Control



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ISS Russian Service Module system is pure DC, fed by shared battery/photovoltaic sources.
•Stiffened by large capacitor bank to maintain 28-29 VDC.

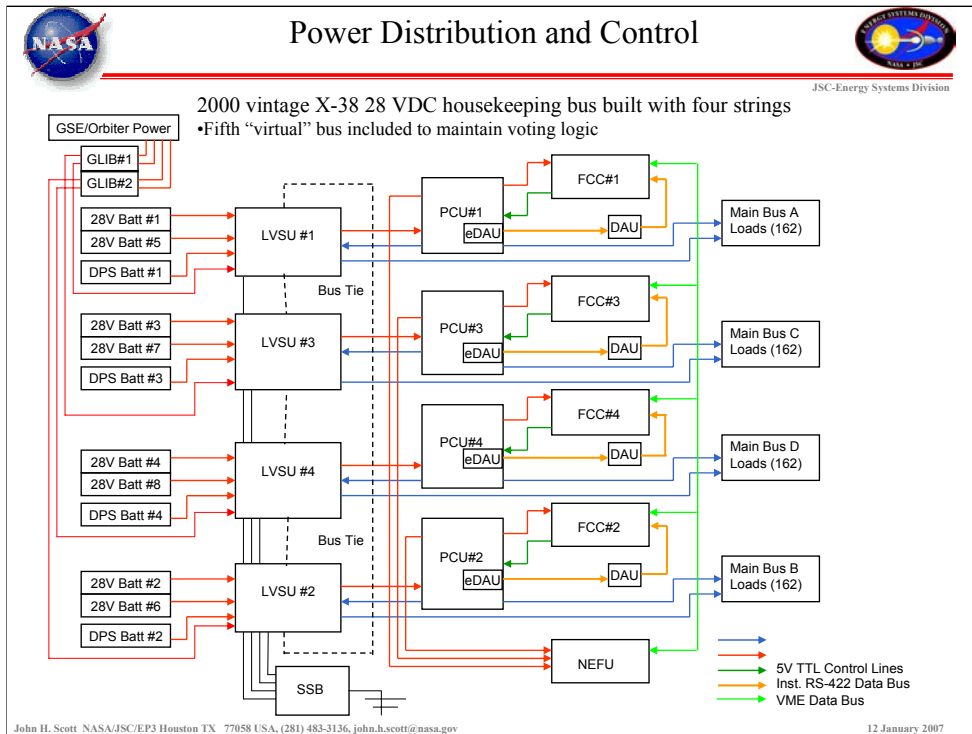


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Russian Soyuz & ISS systems use a large 0.6 F capacitor for stiffening

- Solar arrays share load with Ni-Cd batteries with active control of strings
- Battery/photovoltaic unit feeds ONE large bus bar with capacitor in parallel and multiple strings to each load (bus is not two fault tolerant end-to-end).



X-38 28 V bus took redundancy management for power to a higher level than Shuttle.

- Unregulated bus
- Virtual "5th" power string used to maintain voting logic in case of two strings going down.



Power Distribution and Control

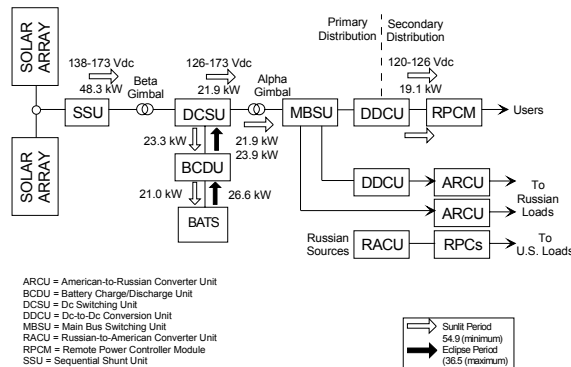


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ISS USOS compromised among many new requirements

- Long cable runs
- Changing configuration
- Shared photovoltaic/battery source

Trades between specific power and development risk/cost resulted in two stage, regulated DC bus: 160 VDC primary (exterior); 120 VDC secondary (pressurized volumes)



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Space Station early development in the 1980's dealt with new requirements (long cable runs, wide voltage range from photovoltaic/battery) and hardware options (more effective magnets for brushless DC motors).

• Traded between three radically different power distribution options:

- 20 kHz 116 VAC offered minimum transmission losses, minimum transformer mass, and crossover switching, but required flat cables (“wave guides”) to reduce reactance, presented new EMI potential, required new connector development)
- 400 Hz 116 VAC offered aircraft heritage, reduced transmission losses but presented low frequency EMI issues in “Free Flyer” platforms initially planned (needed common bus for ORU interchangeability).
- 160/120 VDC offered acceptable transmission losses and EMI environment in all vehicles

• Two buses on each Photovoltaic module. Eight at Assembly Complete. Nominally 78 kW provided by USOS at user interface

- Load redundancy management requires complicated schemes
- 20 kHz solid state switches in SSU shunt power from the 82 strings available in each wing to follow load.
- BCDU bidirectionally switches power to or from batteries depending on power level from arrays.
- MBSUs (some current limited, some not) switch primary bus at 160 V, DDCU step down to 120V secondary which is managed by multiple RPCM (all solid state switching).



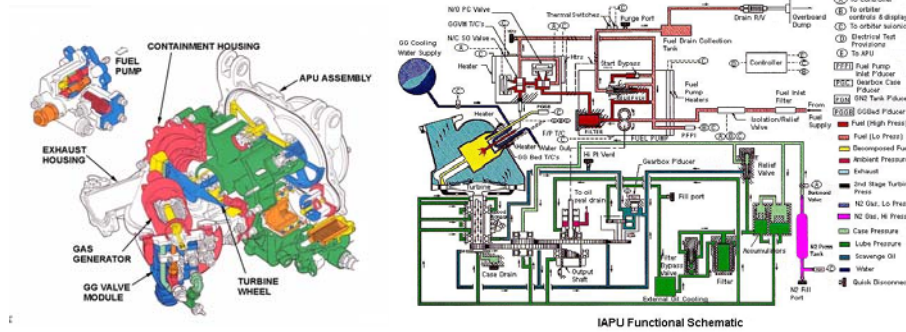
Actuation



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Gas turbine hydraulic pumps deliver highest specific energy solution for launch vehicles

- Thermal challenges on long-duration flights
- Inspection expensive for reusable vehicles



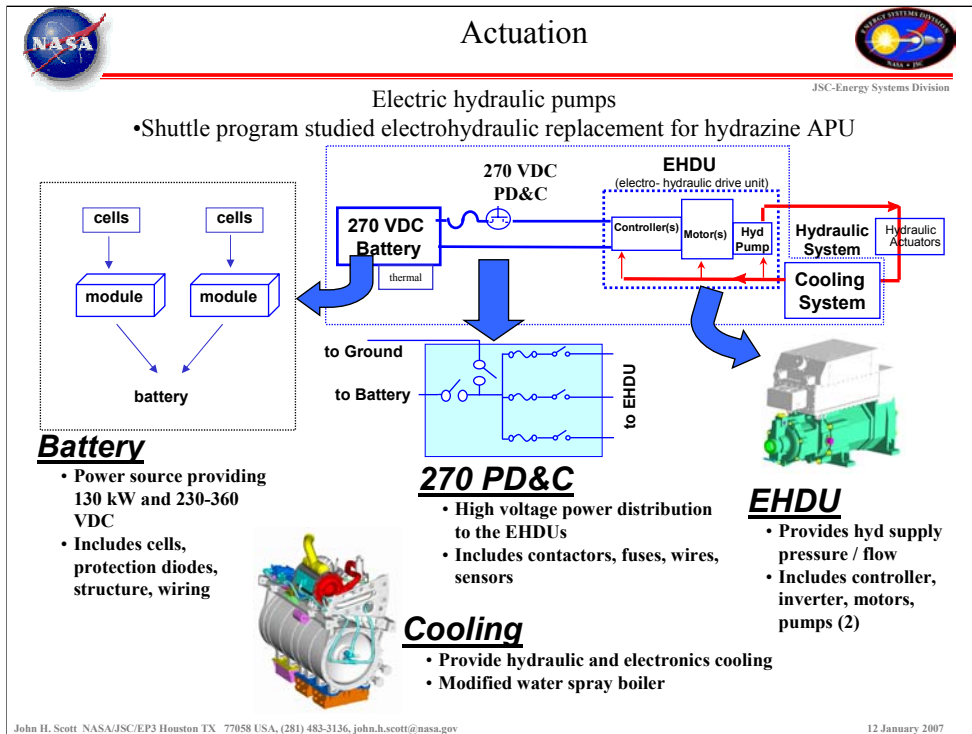
Shuttle Orbiter APU/Hydraulics System

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Hydrazine-fed gas turbine hydraulic pump was highest specific energy actuation solution for Shuttle.

- Three APUs pressurize three cross-strapped hydraulic strings with constant speed, variable volume pump.
 - For aerosurface control, nozzle TVC, and main engine valve control, brakes
 - Elevon actuators two fault tolerant at actuator.
 - Others are single fault tolerant redundancy at each actuator.
 - If two systems fail, all actuators can operate at reduced capability.



- Shuttle electric APU program initiated purely to increase safety and reliability
 - Eliminate hazards of hydrazine
 - Specific energy decreased (2000 lb weight hit at vehicle level)
- Technology program tested all components – 270 VDC system to lower wire weight
 - Cancelled after Columbia drove shuttle retirement in 2010.



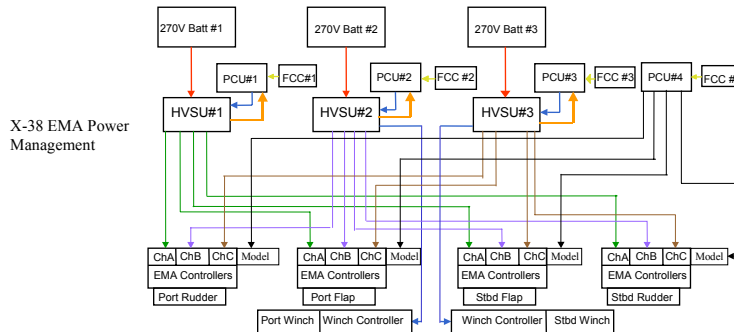
Actuation



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Electromechanical actuation

- Survives long duration missions better than hydraulics



X-38 Rudder and Body Flap Actuators

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- Advent of more effective permanent magnets enabling DC motors, along with advent of solid state switching, have made EMAs attractive vs hydraulic systems.
 - Lower maintenance and more durability than hydraulic systems in aircraft applications.
- For spacecraft applications, optimal systems include high voltage 270 VDC battery fed systems, commutation in ECUs for high speed, low torque (and low inertia) DC motors.
 - Reliability trades between velocity summed and torque summed motors
- For aerosurfaces X-38 EMAs went to three torque summed motors with simulated fourth to maintain voting.
 - All three drove one ball screw on each EMA
- Winch actuators single string.

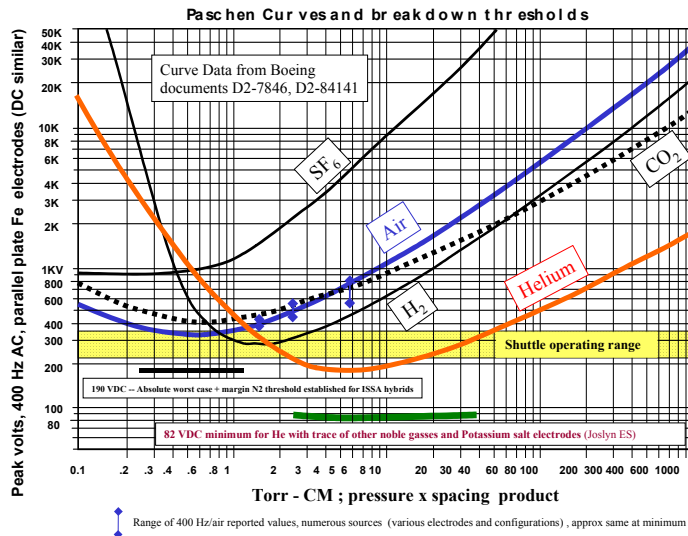


Actuation



JSC-Energy Systems Division

High voltage (270 VDC) systems for electrohydraulics and EMAs present Corona risks ascent ascent and decent.



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Corona design standards exist, but risk is workmanship dependent.

- Corona events in EAPU battery and pump, and in X-38 EMA
- Lack of verified means of checking out long cable runs for corona potential was one factor in Ares upper stage turning away from EMA systems to hydraulics.



Summary



JSC-Energy Systems Division

- Fundamental trade space is well explored and relatively static
- Technology advancements have not improved performance potential of options as much as lowered development cost.
 - Exception: Batteries, DC Motors
- Further R&D can make defined options more accessible to NASA's Exploration Program and expand mission capabilities.