EEC 216 Lecture #10: Power Sources

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Outline

- **Announcements**
- **Review: Adiabatic Charging and Energy Recovery**
- **Lecture 9: Dynamic Energy Recovery Logic**
- **Lecture 9: Power and Clock Waveform Generation**
- **Power Supplies**
- **Batteries and Battery Modeling**
- **Fuel Cells**
- **Power MEMS**
- **Next Time: Energy Harvesting**

Announcements

- **Design Project 2 due Monday, March 3, at 5 PM in instructor's office**
- **Final project proposals also due Monday**
  - Email a brief description (1 paragraph) of what you plan to evaluate for the final project
  - Attach a paper or papers from the literature that describes the circuit/technology/etc. which is the focus of the project

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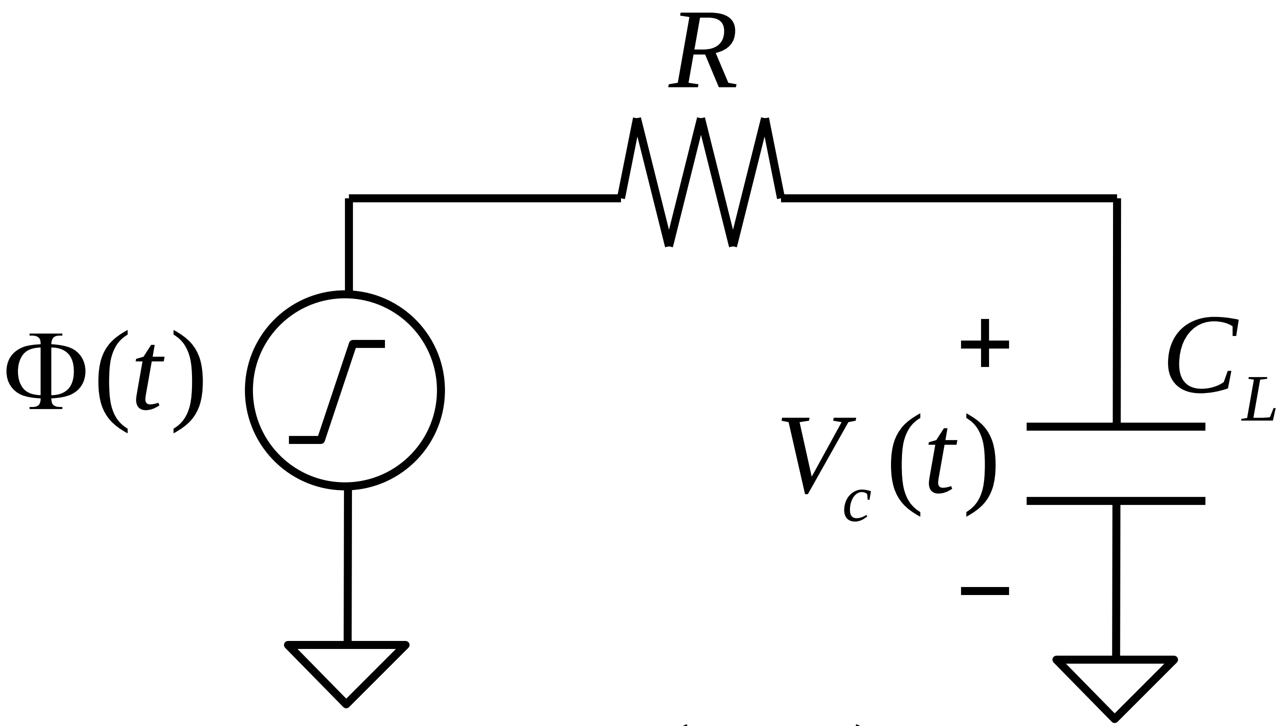
Adiabatic Charging Analysis



$$\Phi = RC\left(\frac{dV_c}{dt}\right) + V_c$$

- **Solve differential equation assuming input is voltage ramp with duration T**

Energy Dissipated With Ramp Driver

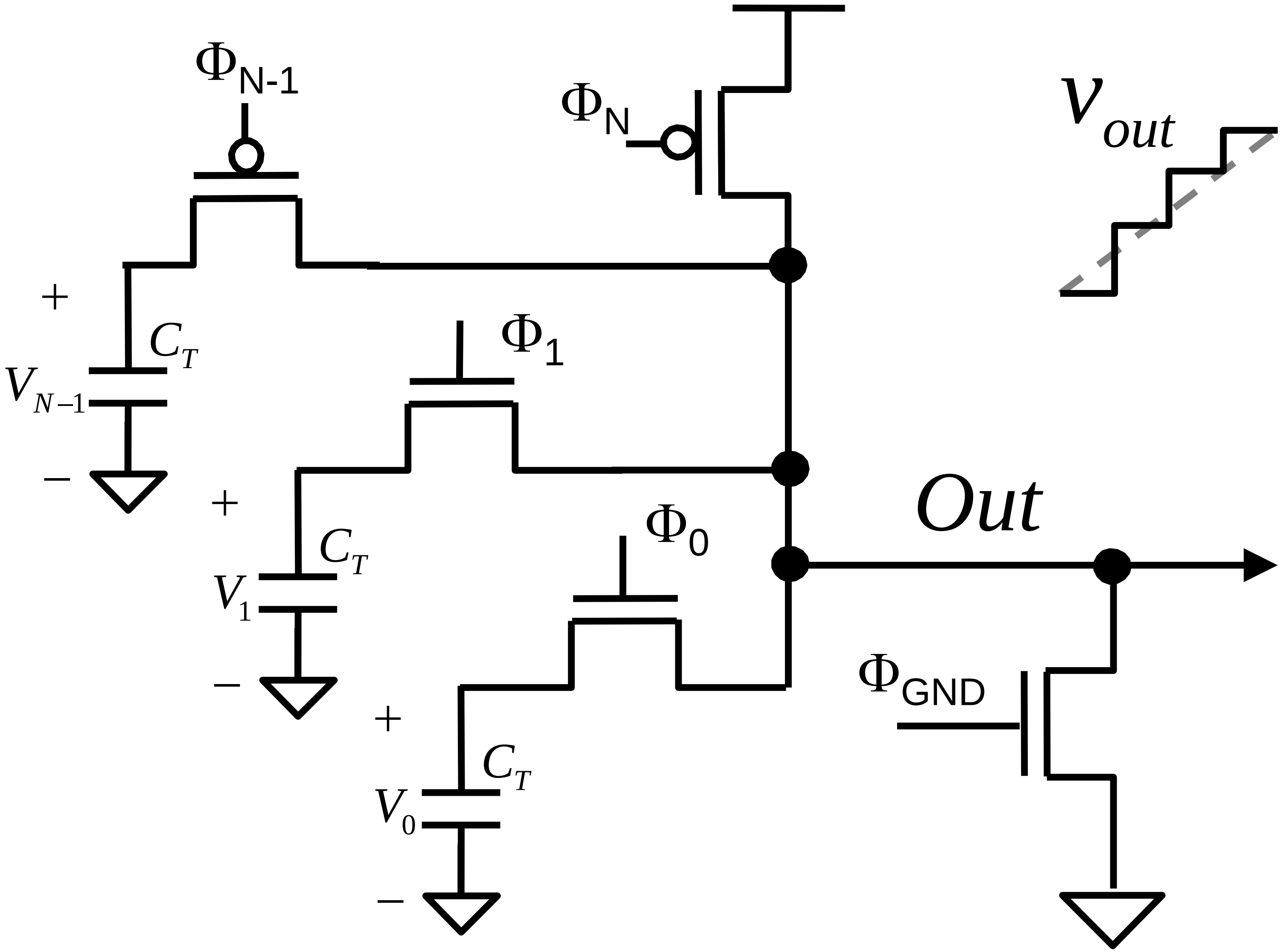
$$E_{diss} = \int_0^\infty i_R(t)V_R(t)dt = \int_0^\infty \frac{\left(\Phi - V_c(t)\right)^2}{R}dt$$

$$= \int_0^T \frac{\left(\Phi - V_c(t)\right)^2}{R}dt + \int_T^\infty \frac{\left(\Phi - V_c(t)\right)^2}{R}dt$$

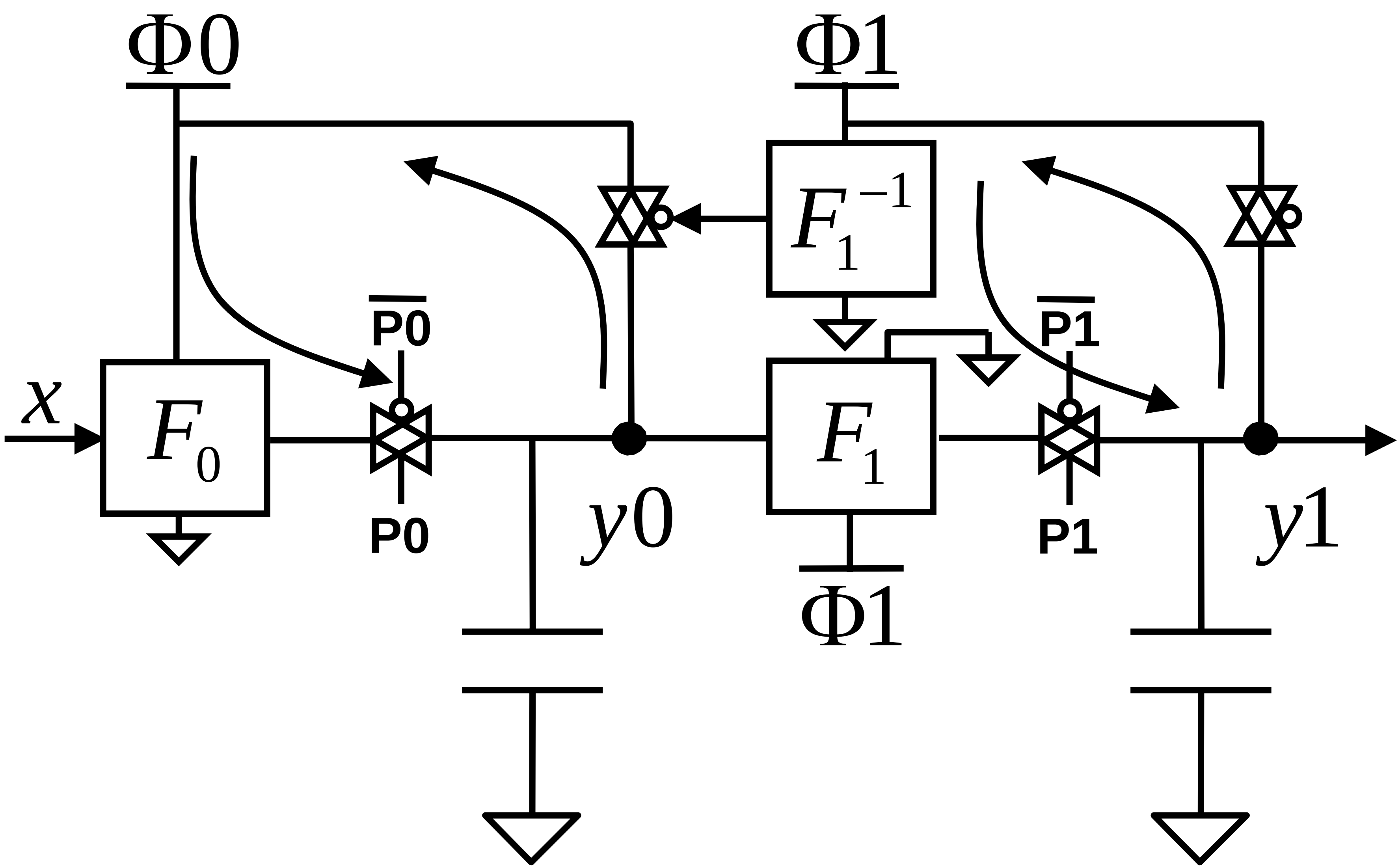
$$= \frac{RC}{T}CV_{DD}^2\left[1 - \frac{RC}{T} + \frac{RC}{T}e^{-T/RC}\right]$$

- **Consider the extreme cases of *RC* with respect to *T***
  - *RC* << *T* implies less energy dissipation

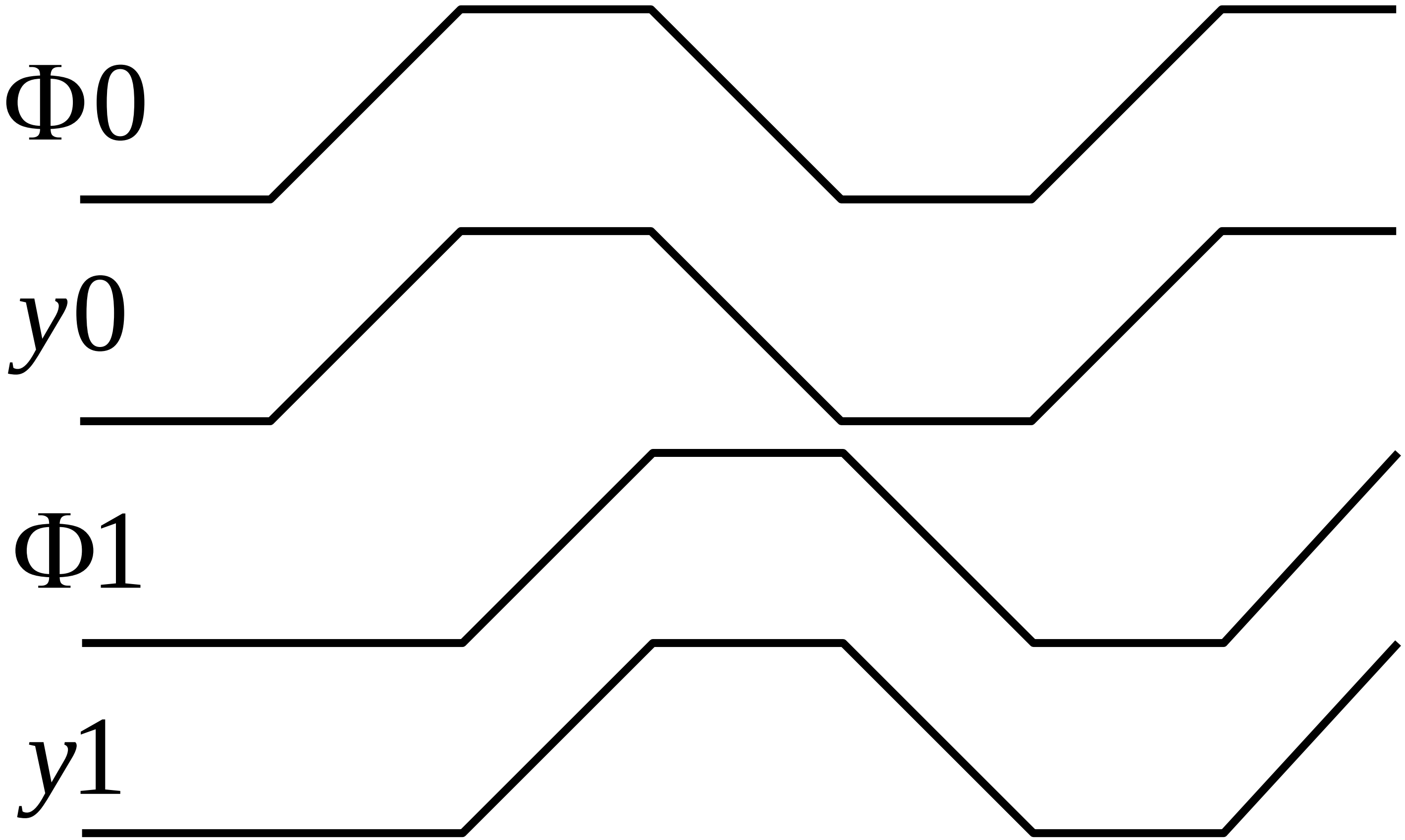
Example Voltage Ramp: Stepwise Charging



Next Stage Controlled Energy Recovery

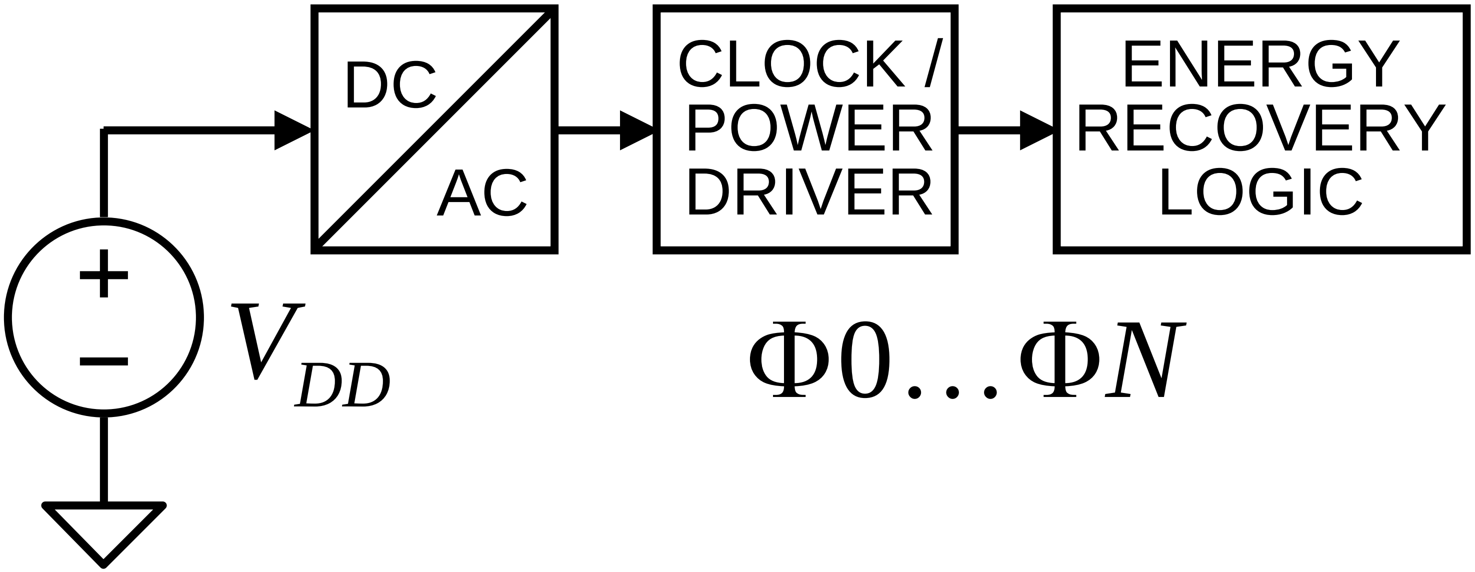


Cascaded Logic Energy Recovery Timing



- **Charge nth stage nodes and then discharge (n-1)th stage nodes**
- **How do we implement the energy recovery phase?**

Energy Recovery System Block Diagram



- **Use circuits to generate power / clock waveforms**
- **Generators must use as little power as possible**
  - Resonant RLC circuits often used in these applications
  - Minimize parasitic losses in power / clock generator

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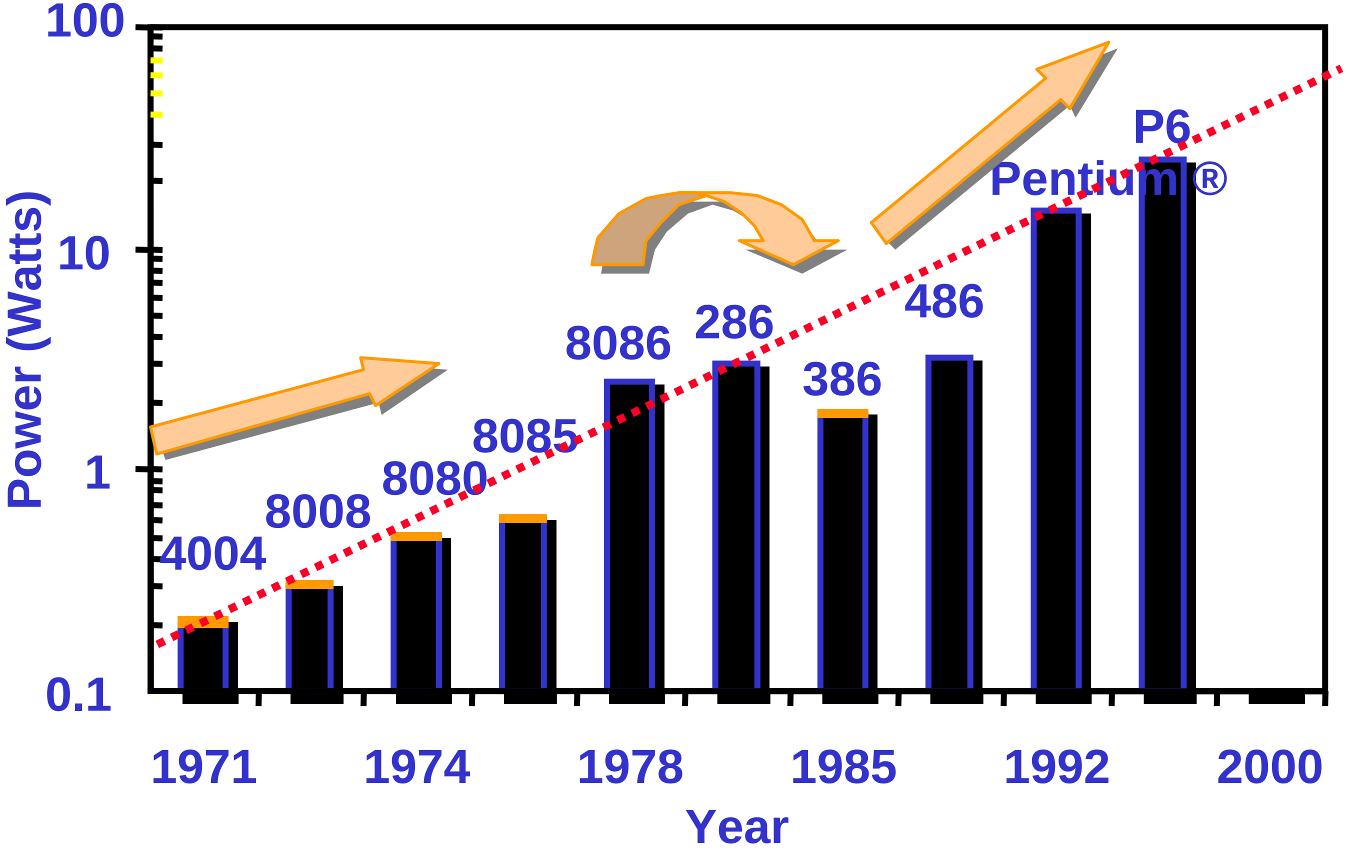
Why worry about power? Power Dissipation

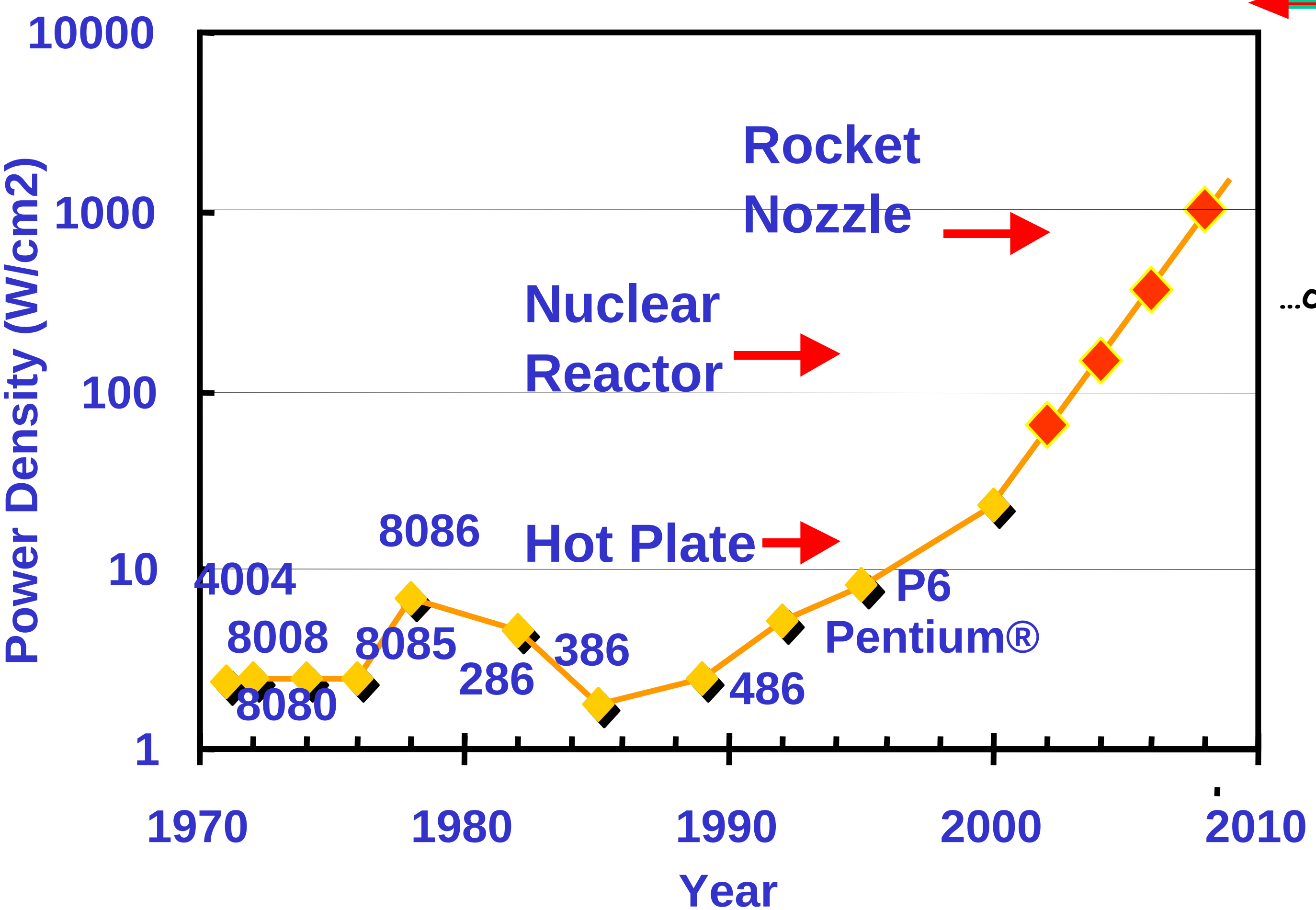
Lead microprocessors power continues to increase



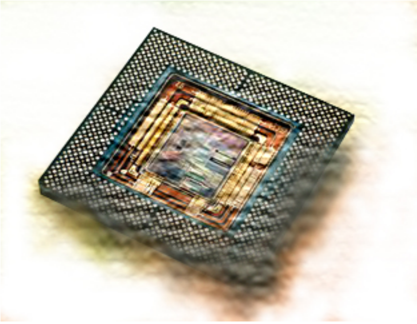
Power delivery and dissipation will be prohibitive

Source: Borkar, De Intel®

Why worry about power? Chip Power Density



...chips might become hot...



Source: Borkar, De Intel®

State-of-the-Art Processor Power

- **Reported at ISSCC 2008**
  - Sun Chip Multithreading SPARC: 65 nm CMOS, 2.3 GHz at 1.2 V, 250 W
  - Intel Quad Core Itanium: 65nm CMOS, 2.0 GHz, 170 W
- **Careful design still keeping power below 100 W**
  - Montecito ISSCC 2005 (dual-core Itanium): 300 W down to 100 W

Previous Processor Power

- **Reported at ISSCC 2004**
  - IBM POWER5: 130 nm SOI, 1.5 GHz at 1.3 V, incorporates 24 digital temperature sensors distributed over die for hot-spot throttling
  - Sun UltraSPARC: 130 nm CMOS, 1.2 GHz at 1.3 V, 23 W typical dissipation
  - IBM PowerPC 970: 130 nm SOI, 1.8 GHz at 1.45 V, 57 W typical dissipation
  - IBM PowerPC 970+: 90 nm SOI, 2.5 GHz at 1.3 V, 49 W typical dissipation

Intel D865GVHZ Motherboard Example

Table 43. DC Loading Characteristics

Mode	DC Power	DC Current at:				
		+3.3 V	+5 V	+12 V	-12 V	+5 VSB
Minimum loading	190.00 W	5.00 A	11.00 A	9.00 A	0.03 A	0.60 A
Maximum loading	286.00 W	11.00 A	15.00 A	13.00 A	0.10 A	1.40 A

- **Minimum load assumes no applications running and no current draw from USB ports or PCI cards**
- **Maximum load assumes heavy gaming application and 500 mA drawn from each USB port, but no PCI add-in cards**
- **Specs for board power delivery system, not specific processor-memory configuration**
- **From Intel Desktop Board Technical Product Specification, Nov. 2003, p. 78**

PC Power Supply Design

- **Multiple output voltages each with different current (power) specs**
  - Supports legacy chip i/o standards, displays, disk drives, speakers, peripherals, modems, etc.
  - Processor supply voltages generated independently of silver box (allows separate optimization, variable voltage design, supports last minute system configuration)
- **System power variable with workload**
  - 1.5X difference between minimum and maximum power
  - Variability impacts power electronics design (load regulation of output voltage)
- **Always minimize cost!**

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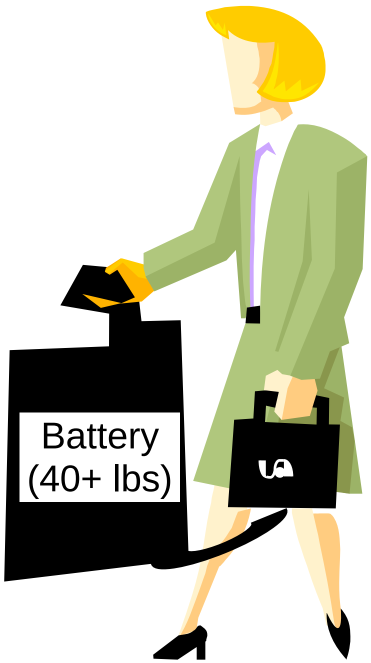
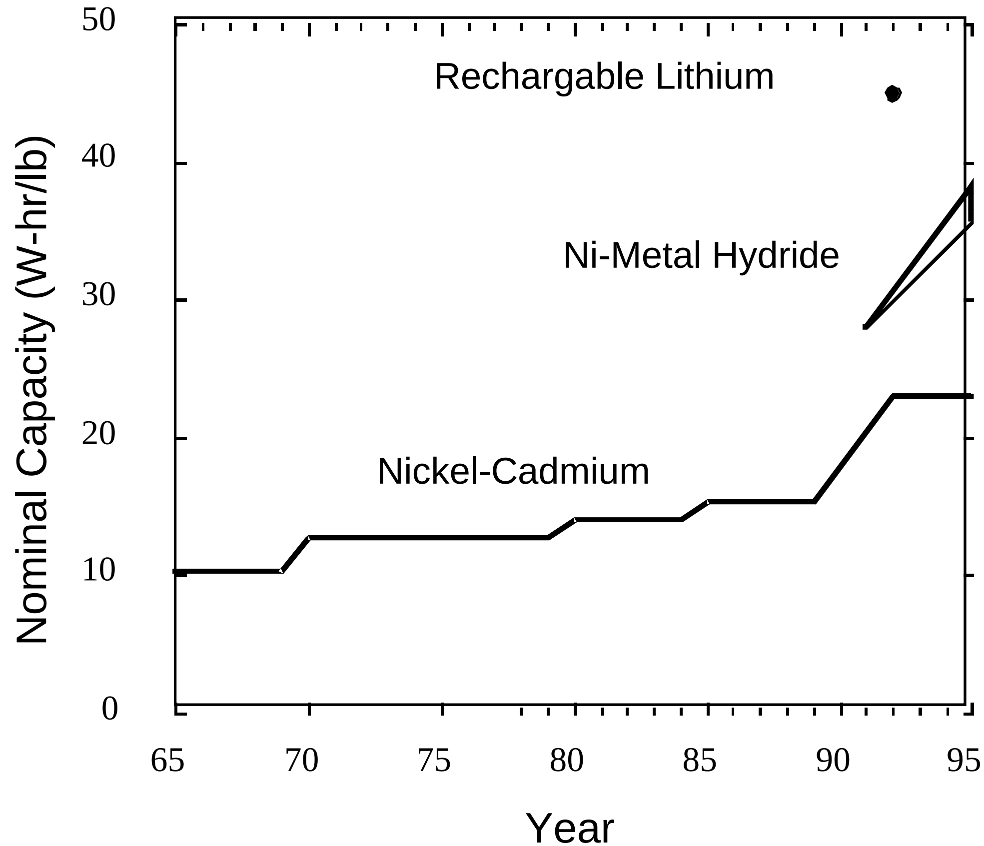
Power Sources for Portable Applications

- **Portable electronics drives need for low weight, small volume, stored energy sources**
  - Want high specific energy or energy per unit mass (Joules / kg)
  - Maximize energy density or energy per unit volume (Joules / cm^3)
  - Must meet peak output power demands
- **Several stored energy options**
  - Electrochemical cells (batteries) with various chemistries
  - Fuel cells possible alternative
  - Power MEMS which also rely on storing energy chemically and then converting it to electricity

Why worry about power ? Battery Size/Weight

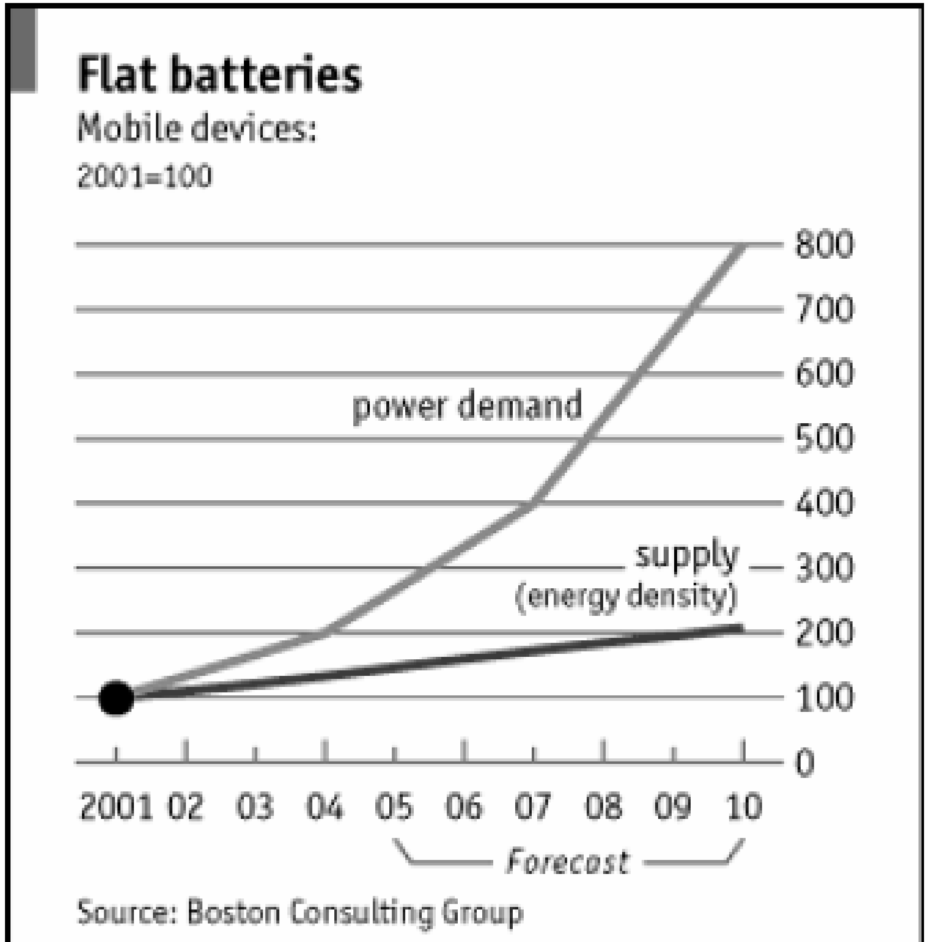




Expected battery lifetime increase
over the next 5 years: 30 to 40%

From Rabaey, 1995

Recent Battery Scaling and Future Trends



- **Battery energy density increasing 8% per year, demand increasing 24% per year (the Economist, January 6, 2005)**

Battery Basics

- **Battery consists of several electrochemical cells**
  - Can be arranged in series (increase output voltage) or parallel (increase output current) or combination
  - Each cell consists of two terminals (anode and cathode) separated by electrolyte
  - These constitute cell's active materials
- **When cell connected to load, oxidation-reduction reaction occurs**
  - Electrons transferred from anode to cathode
  - Transfer converts chemical energy stored in active material to electrical energy
  - Flows as current through external load

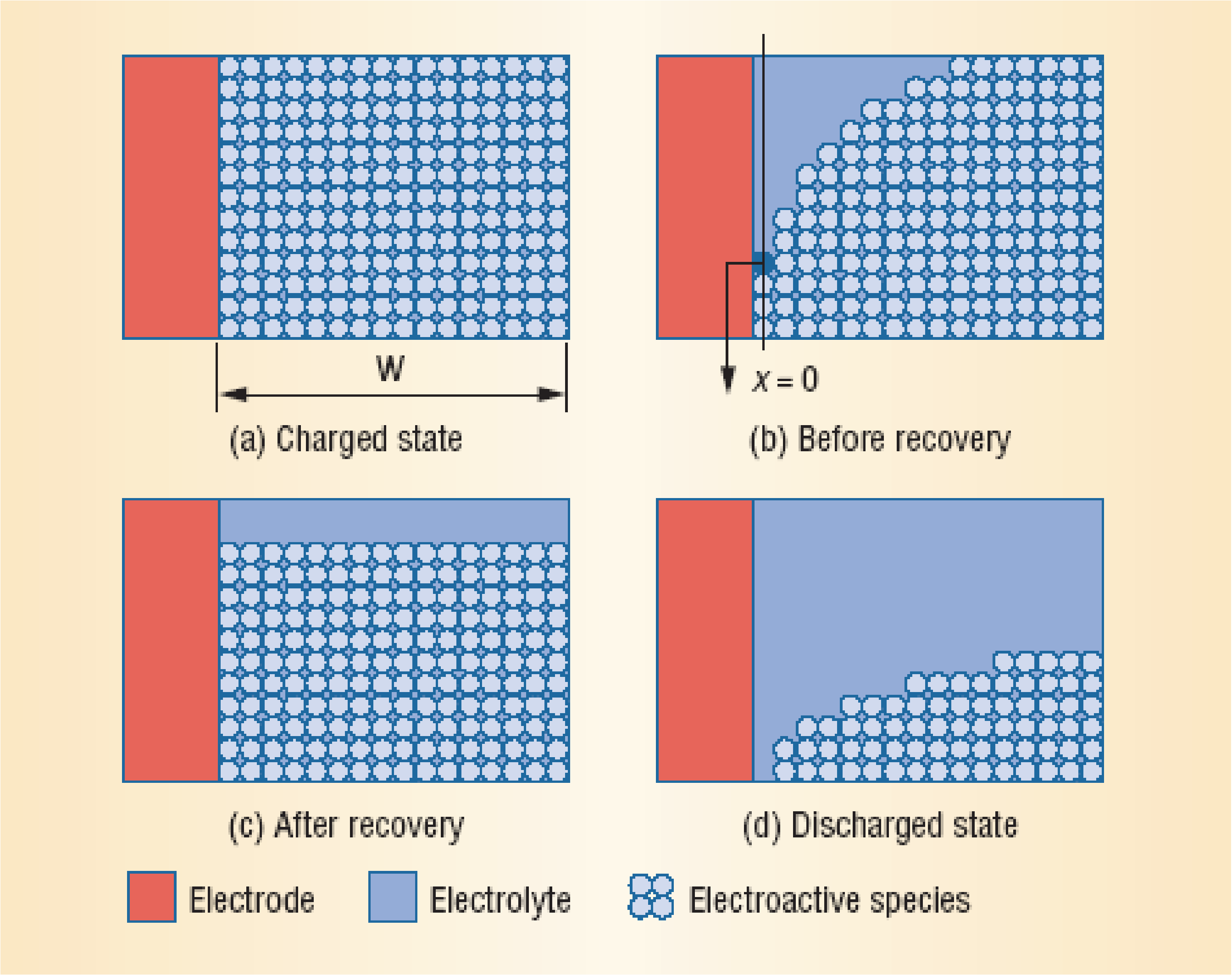
Battery Discharge and Capacity Definitions

- **As battery discharges, output voltage drops**
  - Battery effectively disconnects from load once voltage drops below cutoff
- **Battery capacity defined in charge units (A-h) instead of energy**
  - *Full charge capacity*: capacity remaining at beginning of discharge cycle
  - *Full design capacity*: capacity for new battery
  - *Theoretical capacity*: maximum extractable charge based on amount of active material
  - *Standard capacity*: charge extracted under standard load and temperature conditions
  - *Actual capacity*: charge delivered under specific load and temperature conditions

Rate Dependent Capacity

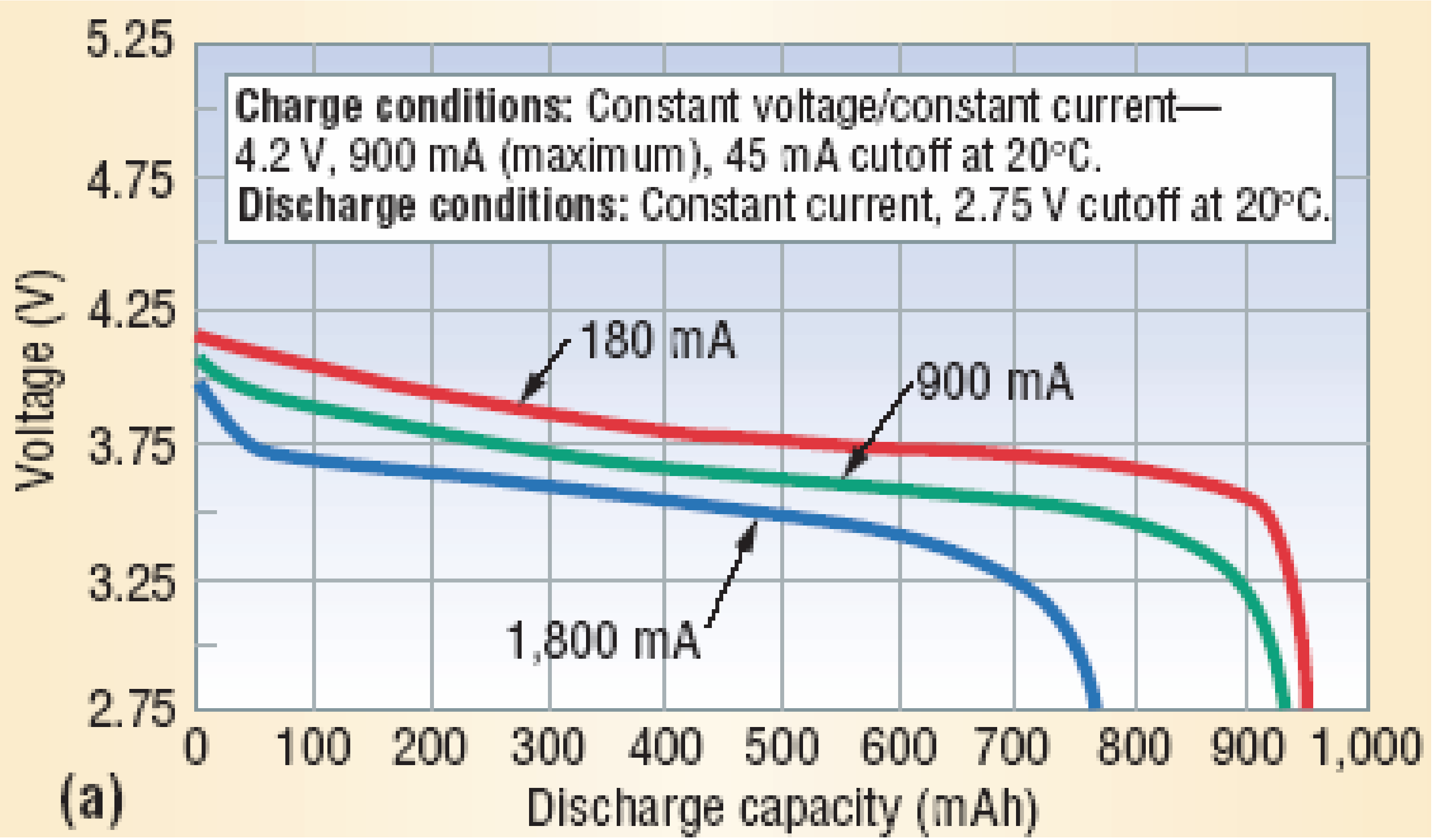
- **Battery capacity decreases as discharge rate increases**
  - When fully charged, electrode surface has maximum concentration of active species
  - Under loading, active species consumed by reaction at electrode and replenished by diffusion from electrolyte bulk
  - Diffusion cannot keep pace with electrochemical reaction, so concentration gradient builds up in electrolyte
  - As load increases, active species concentration at electrode drops below threshold (corresponding to cutoff voltage) and reaction cannot be sustained, eliminating current flow
  - Eventually cell recovers (*charge recovery*) as diffusion flattens concentration gradient
- **For sufficiently low discharge rates, operation remains close to ideal**

Rate Dependent Capacity Operation



- **Rao et al., Computer, Dec. 03**

Lithium-Ion Rate Dependent Capacity

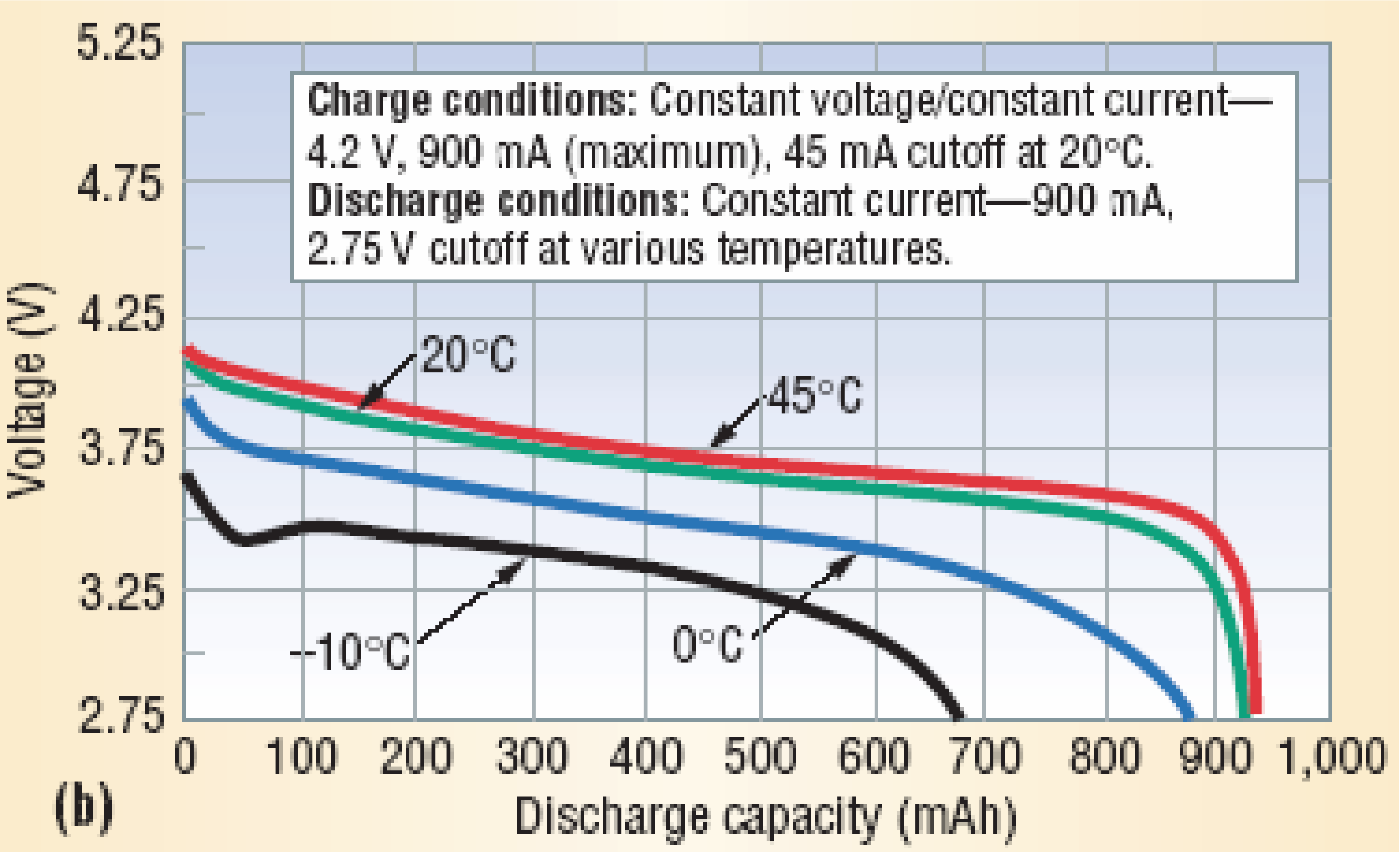


- **Rao et al., Computer, Dec. 03**

Temperature Effect

- **Like any chemical reaction, temperature strongly affects battery discharge behavior**
- **Below room temperature, cell chemical activity decreases**
  - Cell internal resistance increases, reducing full charge capacity and increasing slope of discharge curve
- **At high temperatures, internal resistance decreases**
  - Full charge capacity and voltage increases
  - Higher rate of chemical activity (self-discharge) can offset these other effects and result in less actual capacity
- **Difficult for designer to control temperature**

Lithium-Ion Temperature Effect

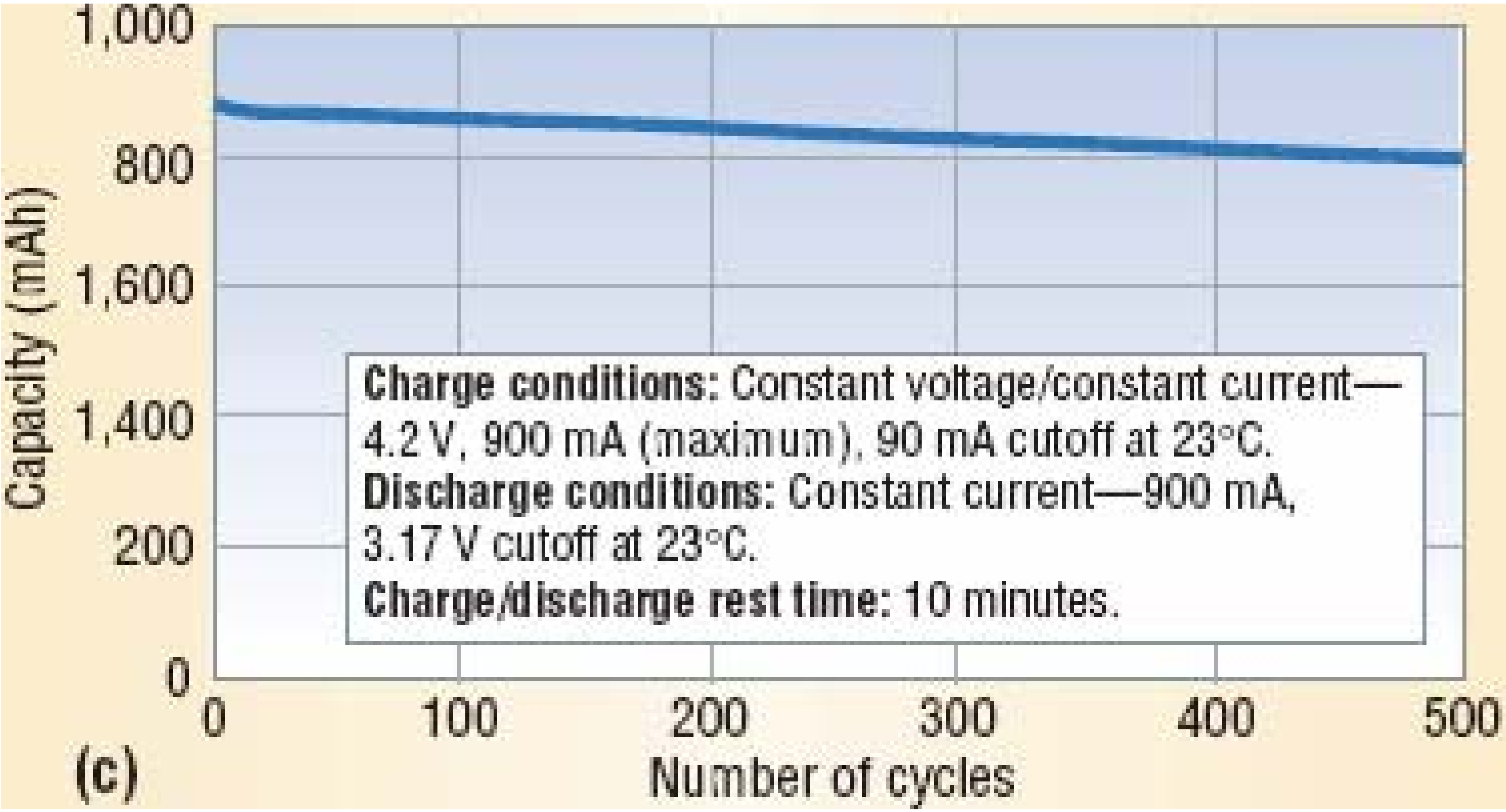


- **Rao et al., Computer, Dec. 03**

Capacity Fading

- **Lithium-ion popular choice for portables**
  - High energy density and capacity
- **Li-ion batteries lose fraction of capacity with each charge-discharge cycle**
  - Unwanted side reactions (electrolyte decomposition, active material dissolution, passive film formation)
  - Irreversible side reactions increase internal cell resistance until battery fails
  - Limit effect by controlling depth of discharge before recharging (constrain battery to only shallow discharges leaving voltage relatively high for recharge)
  - Shallow discharge typically allows battery to undergo more cycles until cutoff voltage finally reached

Lithium-Ion Capacity Fading



- **Rao et al., Computer, Dec. 03**

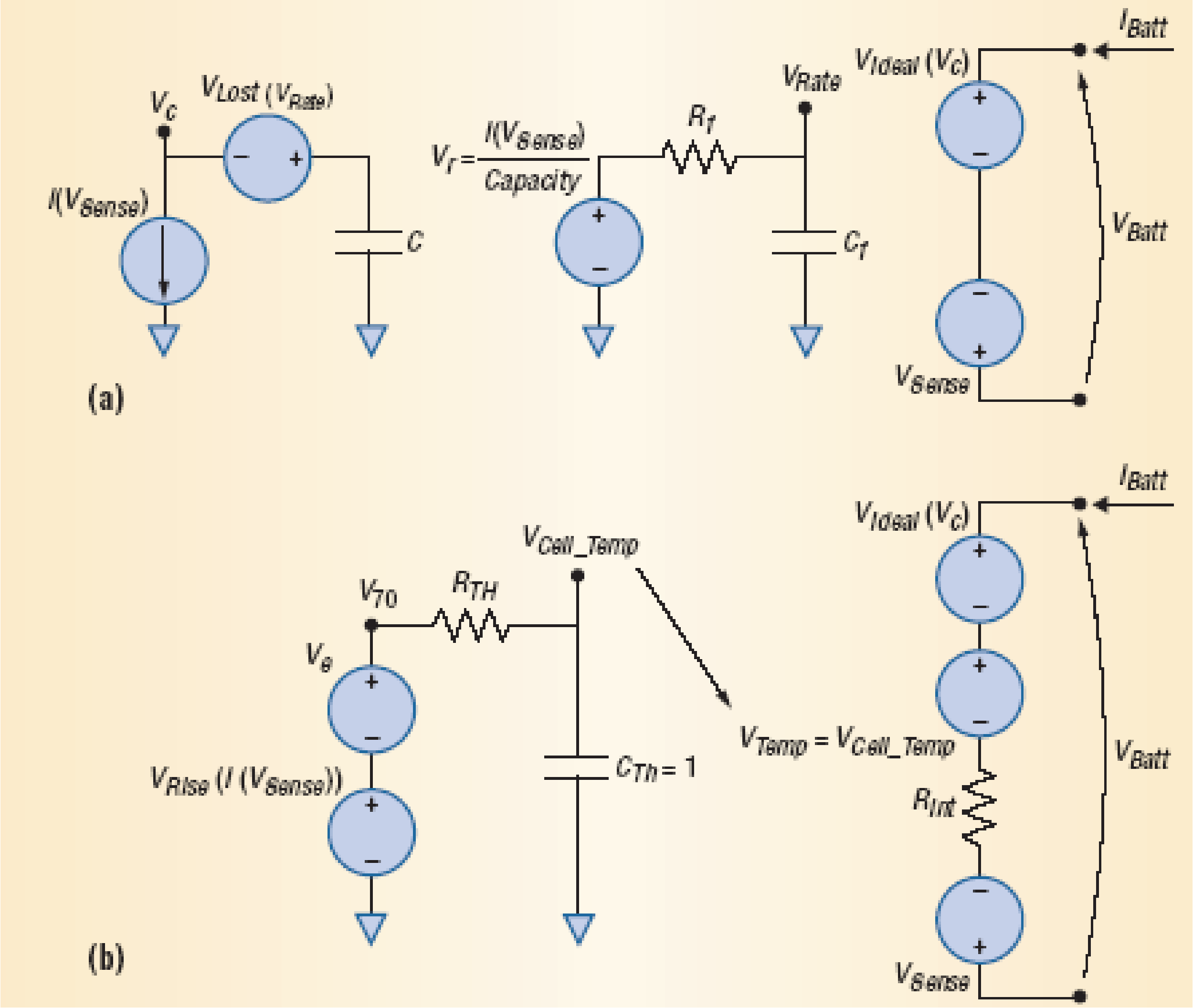
Battery Models

- **Physical models**
  - Most accurate, can be used to optimize battery design, but computationally intensive
  - Differential equations based on isothermal electrochemical model
- **Empirical models**
  - Peukert's Law: $C = LI^{\alpha}$
  - *C* is capacity, *L* is lifetime, *I* is constant current
  - Ideal battery with constant current load yields $\alpha = 1$
  - Exponent provides simple way to model rate dependence
  - Does not model time-varying loads

Battery Models (cont.)

- **Electrical circuit models**
  - Attempt to provide equivalent circuit model for battery
  - Model using linear passive elements, voltage sources, and lookup tables
  - Compatible with HSPICE, Verilog / VHDL
- **Add circuit complexity to capture all effects**
  - Model capacity fading with capacitor whose value decreases linearly with number of charge-discharge cycles
  - Temperature effect modeled as RC circuit with temperature-dependent voltage sources
- **Discrete-time (state) model in VHDL**

Battery Electrical Circuit Models



- **Rao et al., Computer, Dec. 03**

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Fuel Cell Alternative to Battery

- **Nickel-cadmium and lithium-ion batteries increased energy capacity 10-15% per year historically**
  - Estimate another 15-25% improvement in capacity
- **Fuel cells and batteries both generate electricity through electrochemical reactions**
  - Chemical reaction between oxygen and hydrogen or hydrogen-rich substance (e.g., methanol current focus of research)
  - Electrodes draw fuel toward porous membrane
  - Hydrogen-rich material breaks down, releasing hydrogen and electrons
  - Hydrogen reacts with oxygen to form water, electrons flow as current in external circuits

Fuel Cells for Portable Applications

- **Users can add more fuel to continue operation**
- **Research on micro fuel cells focused on membrane**
  - Proton-exchange membrane (PEM) traditional material but usually too large to be portable
  - Stacks of porous silicon wafers dramatically increases number of generated electrons (proportional to membrane surface area)
  - Other research ongoing on membranes
- **Still being investigated as a practical battery alternative**
  - Challenges include standardization, cost, fuel flammability
  - May reach significant market in next 1-2 years

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Power MEMS Motivation

- Battery Technology Limits
  - Enormous military and commercial demand for something better
  - Metric: W-hr/kg
    - Current Battery Technology ~ 100-200 W-hr/kg
- High Density Energy Sources
  - Propulsion
  - Heat Generation
  - Refrigeration
    - Chip Cooling

- **Schmidt, ISSCC 03**

Power Generation MEMS Options

- Energy Scavenging/Harvesting
  - Vibration
  - Heel Strikes
  - Residual Heat
- Fuel Burning
  - *ThermoElectric (TE)*
  - ThermoPhotoVoltaic (TPV)
  - Fuel Cells
    - Requires Hydrogen Source
  - Rotating (moving) Machinery
    - ***Microturbines***

- **Schmidt, ISSCC 03**

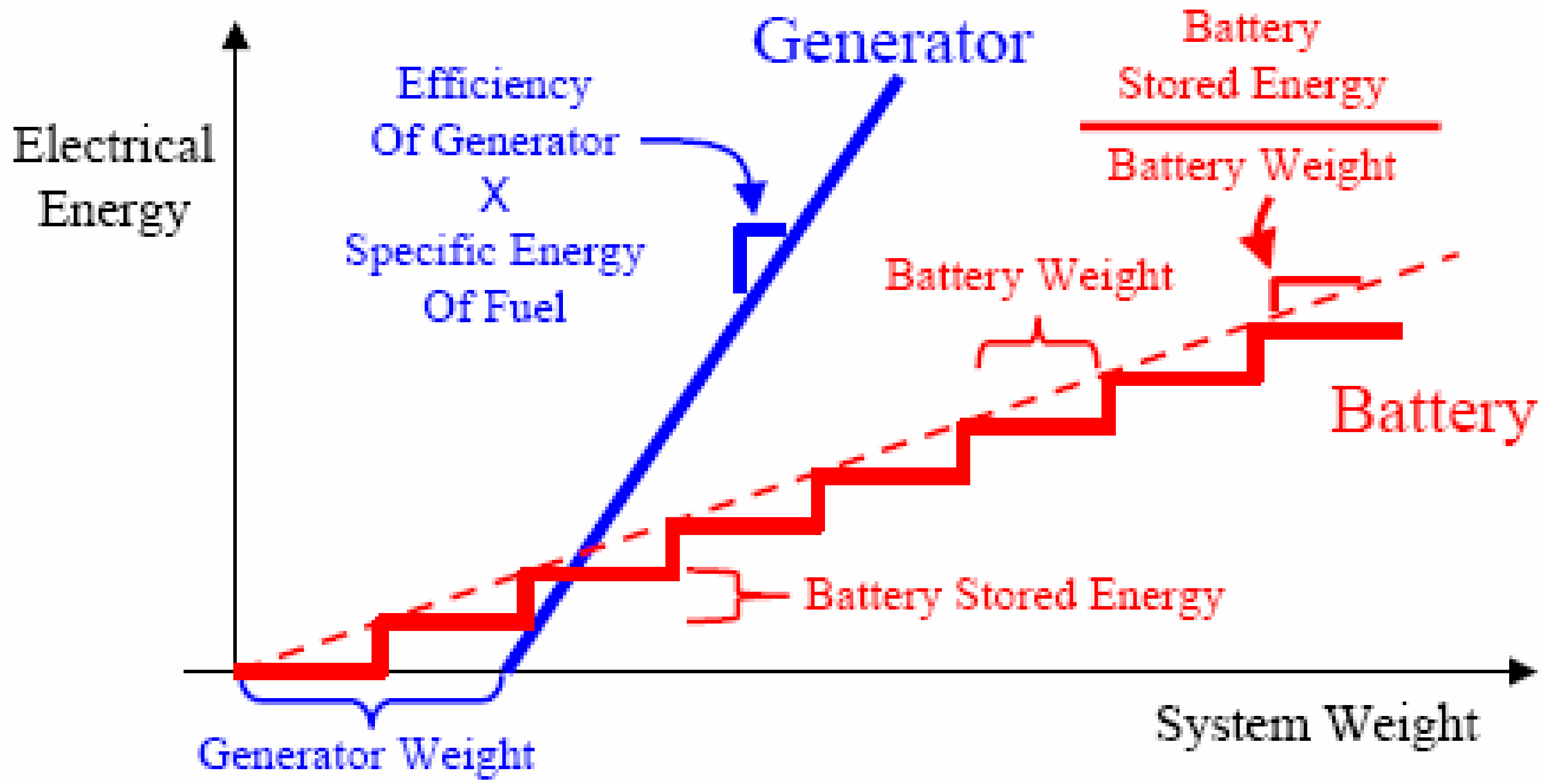
Batteries vs. Fuel

- Batteries
  - ~500 Watt-hours per kilogram for Primary
  - ~175 W-h/kg for Secondary (Rechargeable)
- Fuel Combustion
  - ~39,000 W-h/kg for Hydrogen
  - ~14,000 W-h/kg for Propane or Butane
  - ~12,000 W-h/kg for Gasoline
  - ~6,000 W-h/kg for Methanol
- ***The Challenge:***
  - ***Efficient, Lightweight Conversion***

Courtesy: Franz, Schaevitz, Lilliputian Systems

- **Schmidt, ISSCC 03**

Fuel Burning Advantages vs. Batteries



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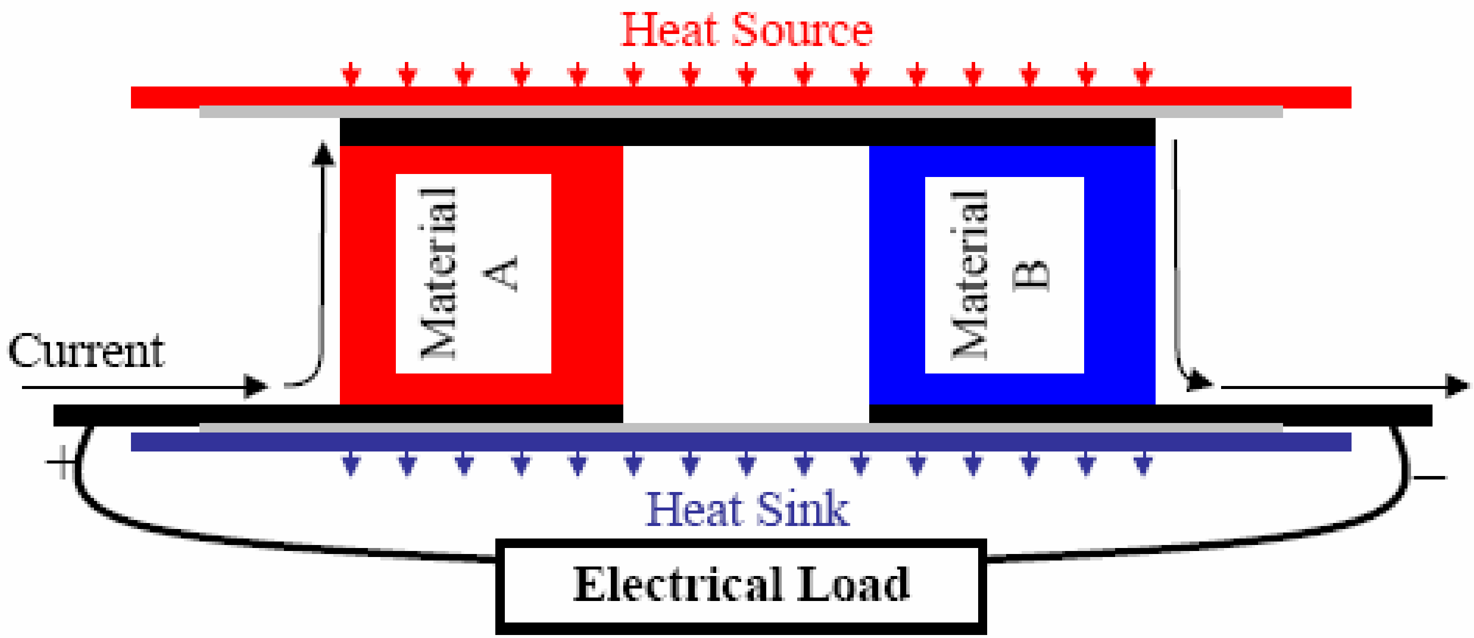
Thermoelectric Generators



Passive Device

Fuel Insensitive

High Power Density

- Well-Established Macro-Scale Technology

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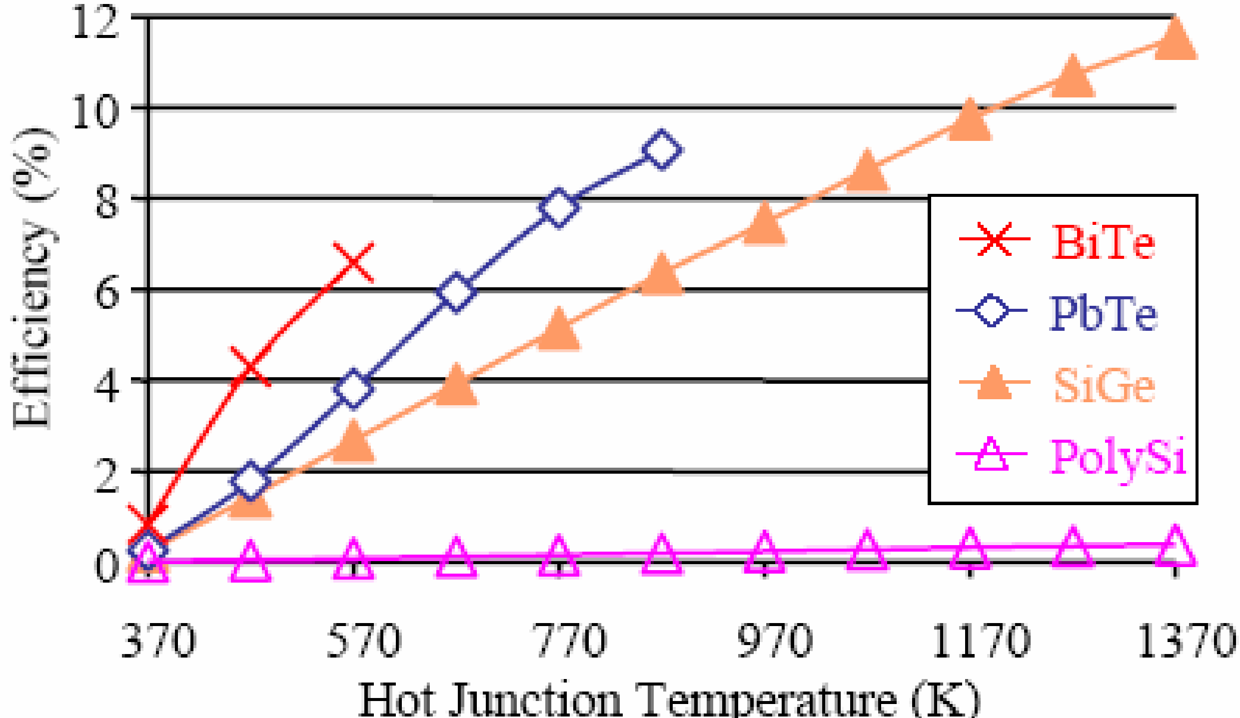
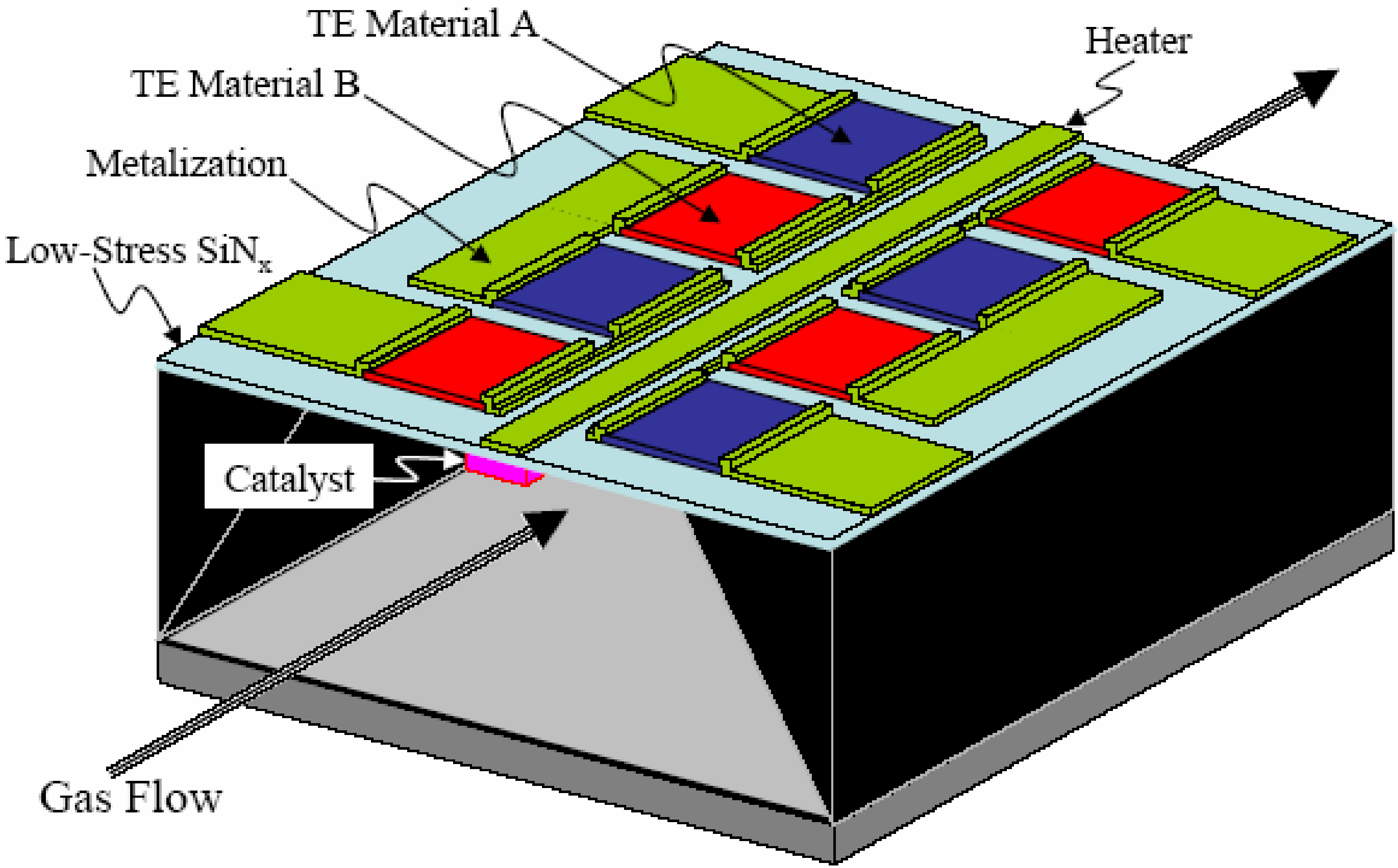
Thermoelectric Generation Materials



- SiGe:
  - Readily Available Semiconductor
  - High Efficiency
  - High-Temperature Operation

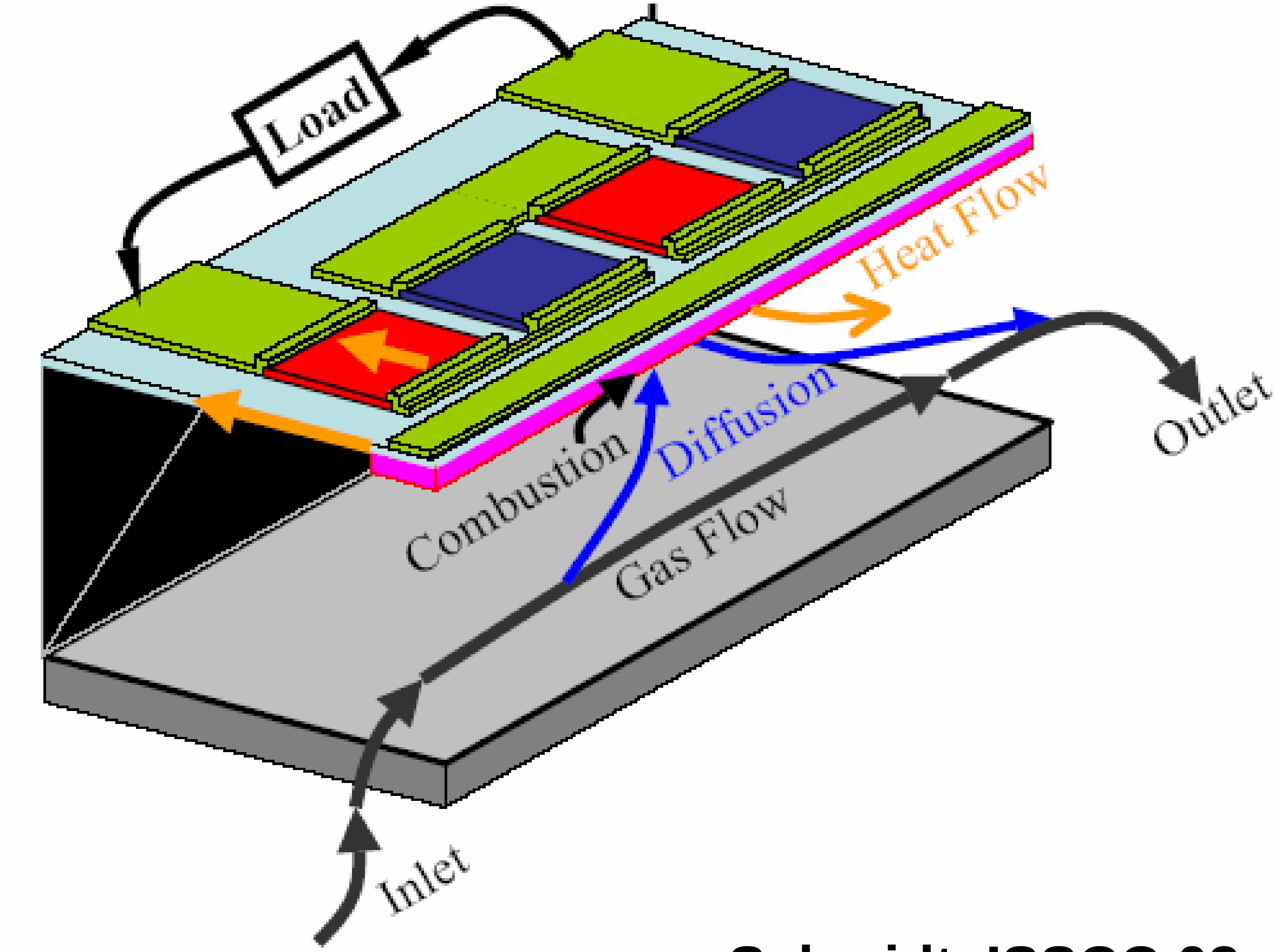
- **Schmidt, ISSCC 03**

Membrane Based Thermoelectric Generator



- **Schmidt, ISSCC 03**

Generator Operation

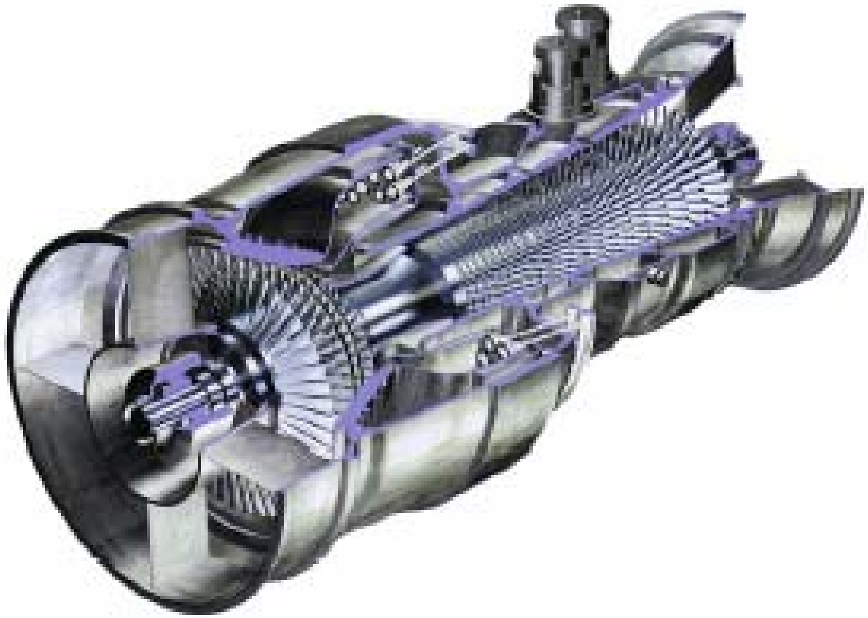


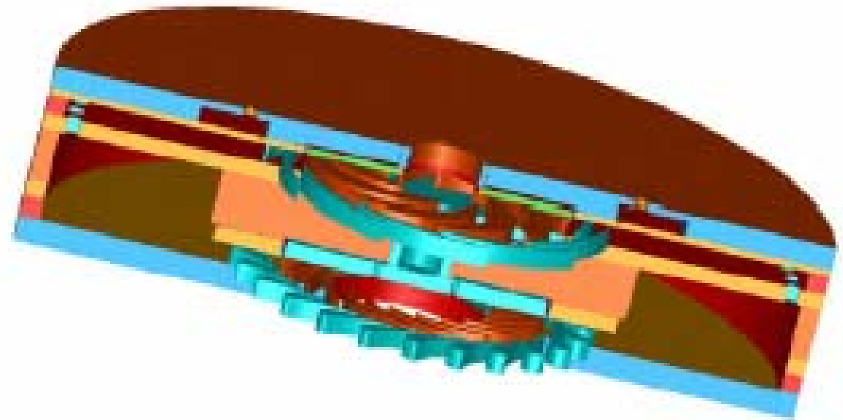
- **Schmidt, ISSCC 03**

Thermoelectric Generator Efficiency

- **Efficiency of thermoelectric generator inadequate**
  - High temperature region localized to membrane
  - Heat flow from membrane too high for efficient conversion
  - Overall device efficiency around 0.02% at 500 degrees Celsius
  - Biggest loss mechanism is thermal conduction in SiN membrane (without this loss, efficiency boosted to 0.4 %)
  - Running hotter (between 700 and 900 degrees Celsius) raises efficiency to 10 %, superior to batteries
- **Significant optimizations in metal contacts, reaction chamber design**
- **Higher power density option: micro gas turbine**

MIT Micro Gas Turbine Generator

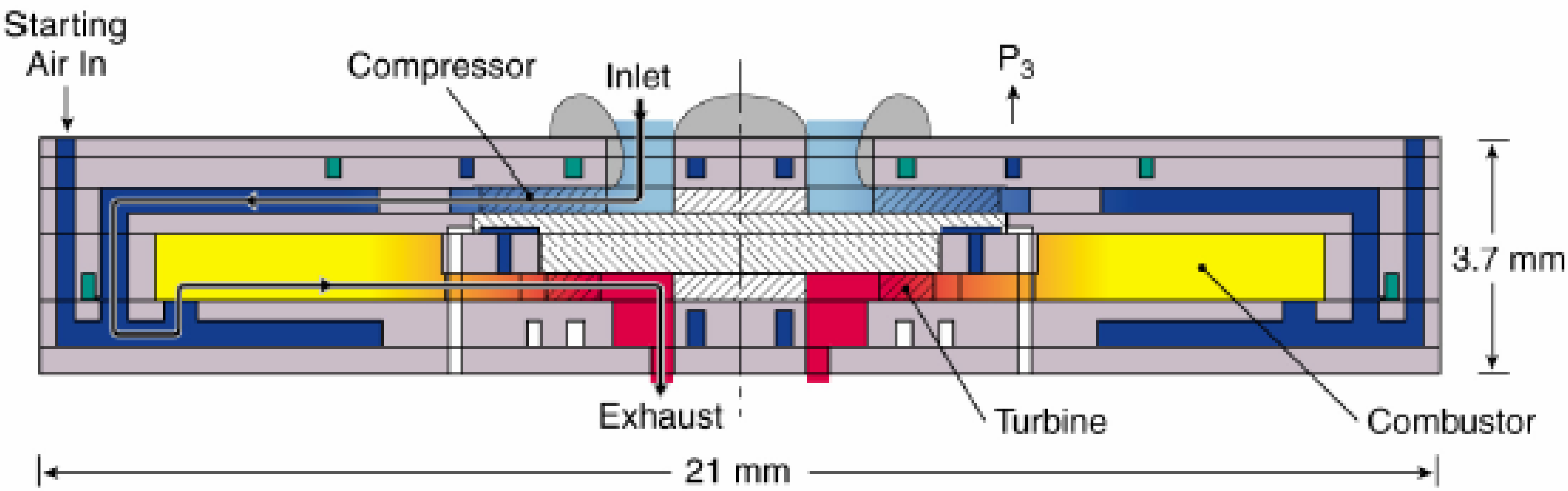




	Micro Turbo Generator	LiSO2 Battery (BA5590)
Power Output	50 W	50 W
Weight	50 grams	1000 grams
Specific Energy	3500 W-hr/kg	175 W-hr/kg

- **Schmidt, ISSCC 03**

Hydrogen Micro Turbine Demonstration



Thrust = 11 g

Fuel burn = 16 g/hr

Engine weight = 2 grams

Turbine inlet temp = 1600°K (2421°F)

Rotor speed = 1.2×10^6 RPM

Exhaust gas temp = 970°C

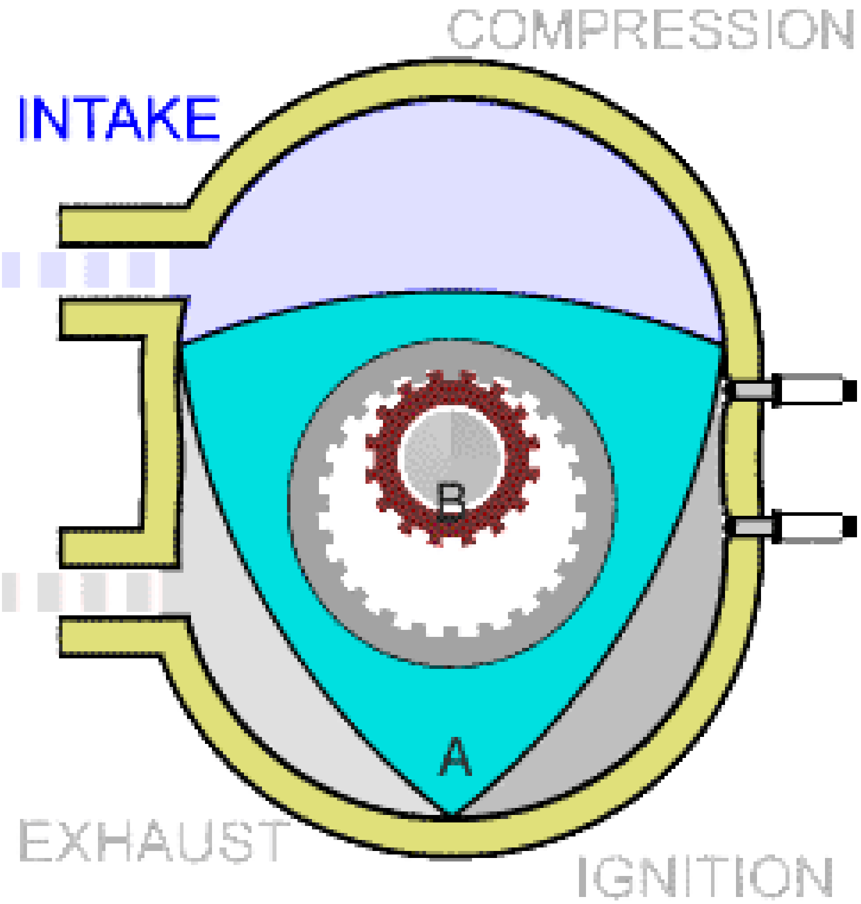
- **Schmidt, ISSCC 03**

Micro Turbine Technical Challenges

- **High speed rotation (greater than 1 Million RPM)**
  - Constrains fabrication precision
- **Combustion using silicon package (instead of SiC)**
  - Constrains conversion efficiency and packaging
- **Electrical conversion nontrivial**
  - Electrostatic induction (traditionally used electromagnetic induction) and new materials
  - Power electronics for conversion including inductors
- **Manufacturing flow complexity (6 wafers, 25 masks)**
  - Controlling etches

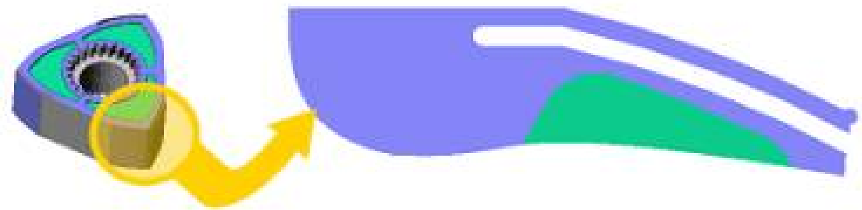
- **Schmidt, ISSCC 03**

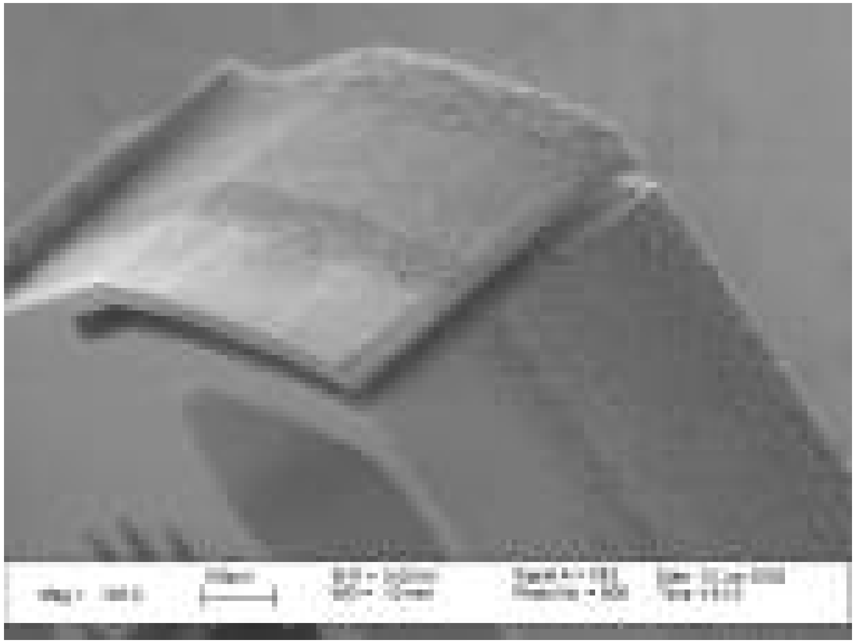
Micro Rotary Engine



• **Wikipedia, GFDL 05**

MEMS Implementation





• **UCB BSAC, 05**