# **1. Power Systems**

• Options for electrical-power production & storage for space missions, current and under development, are shown in the following figure in terms of power vs. mission duration,



Figure 9.1: Spacecraft power systems (Hyder).

- Primary Batteries:
  - · Produce direct current by electrochemistry
  - · Currently used: LiCFx (lithium polycarbon monofluoride) electrolyte
  - · Economical for small spacecraft for missions of relatively short duration.
- Solar PV Battery:
  - · Photovoltaic cell, semi-conductor material, directly converts sunlight to electricity.
  - · Most widely used energy-conversion device for spacecraft
  - Provide relatively high power levels over long duration (up to 10 to 15 years).
  - · Batteries required to provide power during eclipse.
- Radioisotope-Thermoelectric Generators (RTGs):
  - · Compact and continuous source of power
  - Used in deep-space missions over several decades
  - Considered nuclear fuel but relatively easy to handle safely: Curium-244 & Plutonium-238
    - [strontium-90 less expensive but not safe to handle]
  - High energy particles heat a thermoelectric material that, in turn, produces an electric potential: Lead telluride SiGe (silicon germanium) doped w. phosphorous
- Fuel cells:
  - $\cdot\,$  Produce direct current by chemical reaction of an oxidant and a fuel.
  - Currently used:  $O_2 \& H_2$ .
  - Work as long as supply of oxidant & fuel available.
- Solar Concentrator Dynamic:
  - Mirrors used to concentrate sunlight to heat a working fluid that powers a turbine: Steam Liquid metal, e.g. potassium chloride Gas, e.g. helium, xenon
- Chemical Dynamic:
  - Burn fuel & oxidant, e.g.  $H_2 \& O_2$ ,  $CH_4 \& O_2$ , to power a turbine.

• Power conversion & storage options and status:

Table 9.1: Power system current and estimated performance (Hyder et al.).

System or Component	Parameter	Circa 1985	Estimated 2000
Solar-Battery Systems	Power Output	5 kW	100 kW
	Specific Power	10 W/kg	50 W/kg
	Solar Array-Battery Costs	\$3000/W	\$1000/W
Solar Cells and Arrays	Cell Power Output	5 kW	100 kW
	Cell Efficiency (in space)	14%	25%
	Array Specific Power	35 W/kg	150W/kg
	Array Design Life (LEO/GEO)	5yr/7yr	10yr/15yr
	Array Specific Cost	\$1500/W	\$500/W
Batteries			
Primary			
AgZn	Energy Density	150W-hr/kg	
	Design Life	2 yr	
LiSOCI,	Energy Density	200W-hr/kg	700 W-hr/kg
	Design Life	3 yr	5 yr
Secondary			
NiCd (LEO)	Energy Density	10W-hr/kg	
NiCd(GEO)	Energy Density	15 W-hr/kg	
NiCd (LEO/GEO)	Design Life	5yr/10yr	
NiH <sub>2</sub> (LEO)	Energy Density	25 W-hr/kg	
NiH <sub>2</sub> (GEO)	Energy Density	30 W-hr/kg	
Auclear Power			
Reactors	Power Level	10kW	10kW
	Specific Power	10W/kg	10W/kg
	Efficiency	10%	10%
RTG	Power Level	2 kW	2 kW
	Specific Power	6 W/kg	10W/kg
	Efficiency	8%	12%
ypical Overall System Parameters	-		
	Power	12 kW	25kW
	Voltage	28 V	50V
	Frequency	DC	DC/AC
	Cost -on-Orbit	~\$1000/kW-hr	
	Radiator Specific Mass	20kg/kW	

1 4010 7.2. 1 0 00		iormanee.		
System	Limit, kW	Eff, %	SP, W/kg	Source
Solar-PV	20	15-30	5-10	experience
RTG	1	7-15	7-15	same
Nuclear-TEC	100	7-15	?	projected
		S	SP is specific pow	/er

R&D always seeking improvements:

Example) NASA funding development of solar array design for SP = 100 W/kg.

- Copper-indium-diselenide thin-film PV cell

- Low-mass structure

- Basic Power System
  - · A general system is shown in the following block diagram,



Figure 9.2: Power system block diagram (Patel).

- System <u>Voltage</u>
  - · Initial spacecraft designed for 28 VDC (automotive typically 12 VDC).
  - Higher the power requirement  $\rightarrow$  higher the operating voltage to reduce losses, i.e.

P = IV V = IR I = current, amperes R = resistance, ohms

$$P_{loss} = I^2 R$$
 in conductors

For fixed power: Higher the voltage, lower the current, lower the loss.

• <u>Standard</u> distribution ("bus") <u>voltages</u>:



Figure 9.3: Bus voltage versus power level for several spacecraft (Patel). LM A2100: Communications satellite LM7000: Communications, Intelsat, 1998 BSS702: Communications, VSAT, 2001 ISS: International Space Station SP-100: Space Power 100 kW (program canceled)

- Rules-of-thumb for bus voltage in LEO orbits:
  - 1. Above ~160 V, solar-array current-leakage to space plasma (negatively charged electron field) starts to increase exponentially, with electric <u>arcing</u> above ~180 to 200 V.
- At 100 V, for every square meter of exposed conductor area, leakage current ≈ 1 mA. Leakage current increases with voltage.
- 3. Above 160 V, conductors require insulation (additional mass).

#### **Chapter 9**

- Voltage Scaling Law:
  - Design experience has shown empirically,

 $V_{opt} = 0.025 \times P \tag{9.1.1}$ 

where

 $V_{opt}$  = optimum system voltage P = required system power

• Mass Scaling Law:

· An empirical scaling law to estimate mass of a new system, from design experience, is,

$$m_{new} = m_{exist} \times \left(\frac{P_{new}}{P_{exist}}\right)^{0.7}$$
(9.1.2)

where

 $m_{new} = mass of a new system$ 

 $m_{exist}$  = mass of an existing, similar system

 $P_{new}$  = power requirement of the new system

 $P_{exist}$  = power of existing system

• A more detailed system diagram showing various power subsystems is given below,



Figure 9.4: Spacecraft power system block diagram (Hyder et al.)

# 2. Solar PV – Battery System

• The most common electrical-power-generation system for spacecraft is the combination of solarphotovoltaic arrays and batteries as shown schematically in the following figure,



- BAT = batteries
- EPS = electrical power system
- $\alpha = \alpha \text{drive}$ , rotates 360° once per orbit
- $\beta = \beta$  gimbals, rotate  $\pm \beta^{\circ}$  to compensate for the solar  $\beta$  angle

# The PV Cell

- The building block of the solar array is the PV cell:
  - · Diode-type junction of two crystalline semiconductors
  - · Generates electricity directly under sunlight
  - · Photons transferred to electron system of the material, create charge carriers
  - · Charge carriers produce a potential gradient (voltage), circulate as current in an external circuit
  - · Concept illustrated in the following simple schematic,



Figure 9.6: Photovoltaic cell cross-section (Patel).

#### **Chapter 9**

• The <u>conversion efficiency</u> of a PV cell is given by,

$$\eta = \frac{\text{electrical power output}}{\text{solar power incident on the cell}} = \frac{IV}{P_{SF}}$$
(9.2.1)

•Conversion efficiency for three <u>common PV cell materials</u>: Silicon (Si) 12-14%

Gallium arsenide/Germanium	
(GaAs/Ge)	18-19%
GaInP2/GaAs/Ge	24-26%

• The useful energy absorption of the sunlight spectrum for silicon is illustrated in the following figure,



Figure 9.7: Sunlight spectrum and useable photovoltaic spectrum.

• About two-thirds of solar-radiation energy lies between wavelengths,  $\lambda = 0.4 - 1.1 \ \mu m$ .

- Silicon has a <u>cut-off</u> wavelength of about,  $\lambda = 1.1 \,\mu \text{m}$ .
- Radiation absorbed and not converted to electrical power is converted to heat in the cell material Example: A photon of blue light, energy of 3 eV, generates about 0.5 eV of electricity and 2.5 eV of heat.
- Photon energy is given by,

 $e_p = hv$  (9.2.2)  $h = \text{Planck's constant} = 6.626 \times 10^{-34} \text{ J-s}$  v = frequency, cps $v = c/\lambda$  (9.2.3)

and,

where

where

• The complex physics of a PV cell can be represented by the <u>electrical circuit</u> in the following diagram,

c = speed of light =  $2.9979 \times 10^8$  m/s

 $\lambda$  = wave length



Figure 9.8: Photovoltaic-cell equivalent circuit (Patel).

#### **Chapter 9**

• The cell acts as a constant current source shunted by a perfect diode:

- Here,  $I_s$  = source or photo current  $I_d$  = the diode current  $I_{sh}$  = the ground shunt current  $R_{\rm s}$  = internal resistance of the material
  - $R_{sh}$  = resistance to internal current leakage to ground

In an <u>ideal</u> PV cell,	$R_s = 0$ (no series loss)
	$R_{sh} = \infty$ (no leakage to ground)
In a <u>typical</u> silicon cell,	$R_s = 0.05$ to 0.10 $\Omega$
	$R_{sh} = 200$ to 300 $\Omega$

• The current delivered to the external load is,

$$I = I_s - I_d + I_{sh} \tag{9.2.4}$$

• An important parameter for PV cells is the <u>open-circuit voltage</u>,  $V_{ac}$ , and is the case for zero load current, i.e. an open circuit, given by,

$$V_{oc} = V + IR_s \tag{9.2.5}$$

• The diode current is given by the classical diode-current expression,

$$_{d} = I_{o} \left[ e^{qV_{oc}/AkT} - 1 \right]$$
(9.2.6)

where

$$I_{d} = I_{o} \left[ e^{qV_{oc}/AKT} - 1 \right]$$
(9.2.0)  

$$I_{o} = \text{diode-saturation (dark) current}$$
  

$$q = \text{electron charge} = 0.1592 \times 10^{-18} \text{ coulombs}$$
  

$$k = \text{Boltzmann's constant} = 1.381 \times 10^{-23} \text{ J/K}$$
  

$$T = \text{absolute temperature, K}$$
  

$$A = \text{curve-fit constant}$$

• From (3.4) & (3.6), the load current is,

$$I = I_{s} - I_{o} \left[ e^{qV_{oc}/AkT} - 1 \right] - \frac{V_{oc}}{R_{sh}}$$
(9.2.7)

where  $V_{oc}/R_{sh}$  = ground leakage and can be <u>ignored</u> compared to  $I_s \& I_d$ .

• The diode-saturation current is measured by applying an open-circuit voltage,  $V_{oc}$ , to the cell in the <u>dark</u> and measuring the current going to the cell.

• Under sunlight, the <u>diode current</u>,  $I_d$ , is <u>small</u> compared to  $I_s$ .

#### **Chapter 9**

• The *I*-*V* and *P*-*V* curves for a cell in sunlight are shown in the following figures,



Figure 9.9: Photovoltaic-cell current-voltage and power-voltage characteristics (Patel).

- · In figure (a),  $I_{sc}$  is the <u>short-circuit current</u> that is determined by shorting the output terminals and measuring the resultant current under <u>full sunlight</u>.
- · Ignoring the small diode and ground leakage current in (2.7), the <u>short-circuit current</u> is ~ equal to the load current, where the load current is a <u>maximum</u>.
- This is the maximum current a cell can provide.
- · At the bottom right of the curve, at zero current, is the <u>open-circuit voltage</u>,  $V_{oc}$ .

Ignoring ground-leakage current, the open-circuit voltage can be obtained from (3.7) for I = 0, where,

$$I_s = I_o \left[ e^{qV_{oc}/AkT} - 1 \right]$$

or

$$V_{oc} = \frac{AkT}{q} \ln\left(\frac{I_s}{I_o} + 1\right)$$
(9.2.8)

- In practical photocells, the photo current  $I_s \gg I_o$ .
- Under constant illumination,  $I_s/I_o$  is a function of cell temperature.
- Cell <u>output power</u> is the product of load current and voltage. The functional relationship is shown in (b) in the figure at the top.
  - The <u>maximum power</u> of a photo cell occurs at the knee in the *I-V* curve.
  - Solar panels are designed to operate at this point.
  - Solar panels are modeled in the electrical system as a constant-current source, per (a) above.

• Typical photo-cell characteristics:

Material	Vmp, V	Imp, $mA/cm^2$	Pmp, mW/cm <sup>2</sup>
Silicon	0.50	40	20
GaAs	1.0	30	30

- An important effect for solar-array design is PV-cell degradation from <u>radiation</u> of charged particles in space: Protons, electrons, alpha particles.
  - Different particles have different damaging effect on  $I_{sc} \& V_{oc}$ .

- Radiation <u>levels</u> measured in <u>MeV</u> ( $10^6$  electron-volts) for a given period of time.
- Degradation of p/n GaAs solar cells is shown in the next figure for proton fluence,



Figure 9.10: Photovoltaic-cell power output as a function of proton fluence (Hyder et al.).

# 3. Batteries

- A satellite power system with solar arrays has to have energy storage to provide power for eclipse periods.
  - The common method of energy storage is a system of rechargeable batteries.
- Batteries store energy in <u>electrochemical</u> form and are of two basic types:
  - **Primary** The electrochemical reaction is <u>irreversible</u>, i.e. cannot be reused after discharge. Applied in short-duration missions, e.g. sounding-rocket payloads.
  - **Rechargeable** The electrochemical reaction is <u>reversible</u>.
    - Device can be recharged with <u>direct current</u> from external source, e.g. solar array. Applicable to long-duration space missions, widely used.
- The internal construction of a typical battery (cell) is illustrated schematically in the following diagram,



Figure 9.11: Battery cross-section (Patel).

- Electrode plates are positive and negative (negative usually the ground terminal, e.g. auto system).
- $\cdot$  The electrode plates separated by electrical insulator.
- Electrolyte fills volume and provides the electrochemical reaction with the electrode plates.
- · Cell <u>voltage</u> determined by electrochemistry and not on size  $\rightarrow$  current & power = f size .
- Common voltage levels: 1.5 3.5 V when fully charged (varies with degree of discharge).

# **Battery Performance Parameters**

• The following definitions commonly used to compare battery types (mainly the electrochemistry):

**Specific energy** = energy stored per unit of battery mass,  $E_{sp}$ , W-h/kg

**Energy density** = energy stored per unit of volume, W-h/m<sup>3</sup> or W-h/l (per liter) [1 liter =  $1 \times 10^{-3}$  m<sup>3</sup>]

Specific power = power the battery can <u>practically</u> deliver per unit mass, W/kg

**Specific density** = power the battery can <u>practically</u> deliver per unit volume,  $W/m^3$  or W/l

• Internal battery resistance limits the rate that energy, i.e. power, can be discharged.

**Cycle life** = number of charge/discharge (C/D) cycles the battery can deliver and still meet the minimum required voltage (cut-off voltage).

#### **Battery Types**

Battery types identified primarily by <u>electrochemistry</u>, compared by energy density vs. specific energy,



Figure 9.12: Energy density versus specific energy for various battery types (Patel).

Nickel cadmium, NiCd:	Most common type for satellite use up to about the mid-1980s.
Positive electrode:	Nickel impregnated with <u>hydroxide</u> , nickel oxyhydroxide NiOOH
Negative electrode:	Nickel impregnated with <u>cadmium hydroxide</u> (toxic)
Electrolyte:	Potassium hydroxide (KOH)
Nickel hydrogen, NiH <sub>2</sub> :	Most widely used type in the last 20 years, replaced NiCds, higher E <sub>sp</sub>
Positive electrode:	Nickel impregnated with an aqueous slurry (?)
Negative electrode:	Platinum
Electrolyte:	Potassium hydroxide (KOH)
Ni metal hydride, NiMH:	Materials nontoxic, used in a few space missions, used in hybrid autos (Prius)
Positive electrode:	Nickel oxyhydroxide NiOOH
Negative electrode:	Metal hydride (hydrogen absorbing, nontoxic)
Electrolyte:	Metallic hydride (solid)
Lithium-ion, Li-ion: Positive electrode: Negative electrode: Electrolyte:	High energy density (Li, low atomic mass), wide commercial application $LiNiCoO_2$ Mixture of two graphites with non-PVDF binder (?) $LiPF_6$ salt (solid)

Silver zinc, AgO-Zn:	Still used, missions with low number charge/discharge cycles, Apollo moon buggy
Positive electrode:	Silver oxide
Negative electrode:	Zinc
Electrolyte:	Sodium hydroxide (NaOH) or potassium hydroxide (KOH)
Lithium-polymer, Li-poly:	Two commercialized technologies, NASA funding development
Positive electrode:	LiCoO <sub>2</sub> or LiMnO <sub>4</sub>
Negative electrode:	Li or carbon-Li intercalation compound
Electrolyte:	Solid polymer, e.g. polyethylene oxide or polyacrylonitrile

• <u>Performance</u> parameters for several battery technologies are given in the following tables: Table 9.3:Specific energy and power, and energy and power density for various battery types (Patel).

Electro- chemistry	Specific energy (Wh/kg)	Energy density (Wh/l)	Specific power (W/kg)	Power density (W/l)
NiCd	40-5	50-100	150-200	300-500
NiH <sub>2</sub>	4565	35-50	150-200	200-300
NiMH	50-70	140-180	150-200	300-500
Li-ion	90-150	150-250	200-220	400-500
Lithium- polymer	100-200	150-300	>200	>400

Table 9.4: Voltage characteristics for various battery types (Patel).

Electro- chemistry	Cut-off voltage	Discharge voltage	Charge terminate voltage	Remarks
NiCd	1.0	1.25	1.55	Exhibits memory effect
NiH <sub>2</sub>	1.0	1.25	1.55	No memory effect
NiMH	1.0	1.25	1.55	Temperature sensitive
Li-ion	2.7	3.50	4.20	Safe, contains no metallic lithium
Lithium- polymer	2.7	3.50	4.20	Contains metallic lithium
Silver-zinc	1.3	1.50	2.05	Needs good air management to
Cut-	-off voltage	<u>– minimum us</u>	seful discharge v	limit self-discharge rate

- Discharge voltage – average voltage during discharge

- Charge terminate voltage – voltage at end of charge cycle

#### **Battery Characteristics**

• Cell <u>capacity</u> defined in terms of <u>ampere-hours</u> (Ah) at some reference temperature, e.g.  $60^{\circ}$ C,  $C = I \times t$  (9.3.1)

i.e. the product of the amount of current that can be supplied in a given time.

• Voltage is a function of expended capacity or depth-of-discahrge as shown in the following plot,



Figure 9.13: Voltage versus state-of-charge for NiCd and NiH $_2$  battery cells (Patel).

**Chapter 9** 

• Here, SOC is state-of-charge, 
$$SOC = \frac{\text{remaining Ah capacity}}{\text{rated Ah capacity}}$$
 (9.3.2)

• Depth-of-discharge is, 
$$DOD \equiv \frac{Ah \text{ extracted from fully charged state}}{\text{rated Ah capacity}}$$
 (9.3.3)

From (3.2) & (3.3), 
$$DOD = 1 - SOC$$
 (9.3.4)

• The product of voltage and Ah rating gives the <u>energy rating</u> of the battery in Watt-hours,  $E_r = V \times Ah$  W-h (9.3.5)

• The battery nearly a constant-voltage source as shown below in cell voltage vs depth-of-discharge,



Figure 9.14: Cell voltage versus depth-of-discharge for NiCd batteries (Patel).

• The point M represents the "memory" point: A NiCd (nickel cadmium) battery used to 25% DOD "remembers" that point and will not work well beyond that DOD in subsequent use  $\rightarrow$  voltage drop.

#### Charge & Discharge Rate

• In battery lexicon the "rate" of charge or discharge is expressed as a fraction of the capacity.

Example) Charging a 100 A-h battery at 10 A takes 10 hours to 100% SOC. The battery is said to be charging at a C/10 rate.

Discharging the same battery at a C/2 rate means drawing 50 A and will deplete the battery in 2 hours.

• Charge/Discharge Ratio:

$$\left(\frac{C}{D}\right)_{R} \equiv \frac{\text{ampere-hours input for 100\% SOC}}{\text{ampere-hours output}}$$
(9.3.6)

Example) A  $C/D_R = 1.1$  means that the battery requires 10% more ampere-hours for restoring it to a fully charged state than what was discharged.

Charge/discharge characteristics of a battery depends on charge rate, temperature and number of cycles.

#### **Spacecraft Power**

• The charge/discharge cycle for a NiH<sub>2</sub> battery in LEO in terms of cell voltage vs. time for various levels of DOD (discharge rate) is shown in the following figure,



Figure 9.15: Charge-discharge cycle for NiH<sub>2</sub> batteries (Patel).

- Typical charge/discharge cell voltages for NiH<sub>2</sub> batteries:
  - 1.55 V fully charged
  - 1.25 V average during discharge
  - 1.45 V average during charge
  - · 1.10 V at 80% DOD
  - · 1.00 V when fully discharged (cut-off)
- Battery cycle life is a function of DOD and operating temperature as shown in the following figure for NiCd cells,



Figure 9.15: Cycle life versus depth-of-discharge and temperature for NiCd cells (Brown).

#### • Charging Efficiency:

Charging efficiency relates the usable battery capacity to the charging capacity,

$$\eta_{chg} = \frac{\text{ampere-hours stored}}{\text{ampere-hours input at external terminals}}$$
(9.3.7)

Charging efficiency is a function of charge rate and operating temperature as shown in the following figures for  $NiH_2$  batteries,



Figure 9.16: Charging efficiency versus state-of-charge for NiH<sub>2</sub> batteries (Patel).

•Charge efficiency higher for lower charge rate, i.e. compare curves for C/40 (low) to C/2 (high).

•Charge efficiency higher for lower battery operating temperature.

• Energy Efficiency:

In both charge and discharge modes, a small fraction of energy is converted to heat. The energy efficiency of a round-trip charge/discharge cycle is,

$$\eta_{e} \equiv \frac{\text{energy output}}{\text{energy input}}$$

$$\eta_{e} = \frac{V_{davg} \times C}{V_{cavg} \times C/D_{R} \times C} = \frac{V_{davg}}{V_{cavg} \times C/D_{R}}$$

$$V_{davg} = \text{average discharge voltage}$$

$$V_{cavg} = \text{average charge voltage}$$
(9.3.8)

where

 $V_{cavg}$  = average charge voltage C = capacity $C/D_R$  = charge/discharge ratio

Energy <u>efficiency</u> is a <u>function</u> of <u>charge rate</u> and operating <u>temperature</u> as shown in the following figure for a typical NiCd battery,



Figure 9.17: Watt-hour efficiency versus charging rate for NiCd batteries (Brown).

• The energy efficiency increases with charging rate.

• The equivalent electrical circuit to model a battery is,



Figure 9.18: Battery equivalent circuit (Patel).

where the electrochemistry is modeled as a voltage source,  $E_i$ , and the electrolyte and electrodes with a small internal resistance,  $R_i$ .

• The electrochemistry <u>voltage decreases</u> and internal <u>resistance increases</u> linearly with depth-ofdischarge as given by,

$$E_i = E_o - k_V \times \text{DOD} \tag{9.3.9a}$$

$$R_i = R_o + k_R \times \text{DOD}$$
(9.3.9b)

where

 $E_o$  = voltage in fully charged state

 $k_V$  = electrochemistry constant for voltage

 $R_o$  = resistance in fully charged state

 $k_R$  = electrochemistry constant for resistance

The electrochemistry constants are determined from curve fits of test measurements.

• To achieve bus voltage,  $V_B$ , batteries are connected in <u>series</u> where the <u>voltage</u> is <u>additive</u>, i.e.

$$V_B = \sum_{i}^{N} V_i \qquad \text{and} \qquad N = \frac{V_B}{V_i}$$
(9.3.10)

where

 $V_i$  = terminal voltage of individual battery N = number batteries in series to give  $V_B$ 

• Battery voltage,  $V_{bat}$ , as a function of current, I, is given by,

į

$$V_{bat} = E_i - IR_i \tag{9.3.11}$$

• Under increasing load, Pload, battery terminal voltage drops, from the current increase,

$$P_{load} = I^2 R_L \quad \longrightarrow \quad I = \sqrt{P_{load} / R_L}$$

$$V_{bat} = E_i - R_i \sqrt{P_{load} / R_L} \tag{9.3.12}$$

• The operating point is the intersection of,

 $V_{load} = IR_L$  and  $V_{bat} = E_i - IR_i$ 

as shown in the following figure,



Figure 9.19: Load and battery voltage versus current (Patel).

• The preceding figure shows the intersection of the <u>battery line</u> and <u>load line</u> that gives the <u>operating</u> <u>point</u>, P, for the system.

• Maximum power deliverable to the load is,

$$P_{\max} = I_{\max}^2 R_L \tag{9.3.13}$$

From the maximum-power transfer theorem, a battery can deliver maximum power to a DC load when  $R_i = R_L$ , so,  $P_{bat} = IE_i = I^2R_i + I^2R_L = 2I^2R_i$ 

or,

$$P_{\max} = 2I_{\max}^2 R_i \tag{9.3.14}$$

so that maximum power,  $P_{max}$ , <u>deliverable</u> to the load,  $I_{max}^2 R_L$ , is 50%, i.e. half of the power is consumed by  $R_i$ .

Also, summing voltages around the battery-load circuit (see p. 15),

$$E_{i} = I_{\max} \quad R_{i} + R_{L} = 2I_{\max} R_{i}$$
  
or,  
$$E_{i}^{2} = 4I_{\max}^{2} R_{i}^{2} = 4R_{i}P_{\max}$$
  
giving,  
$$P_{\max} = \frac{E_{i}^{2}}{4R_{i}}$$
(9.3.15)

· Batteries not normally run at this condition as it limits their useful life.

• Cell <u>internal resistance</u> is a function of depth-of-discharge per (3.9b) and temperature. The variation of internal resistance with temperature is shown for a 50 A-h NiH<sub>2</sub> cell at 100% state-of-charge (SOC), i.e. fully charged, in the following figure,



Figure 9.20: Cell resistance versus temperature (°C) for NiH<sub>2</sub> batteries (Patel).

# **Battery Design**

• The following diagram shows the construction of a <u>nickel-hydrogen</u> cell for a Comsat (communications satellite in GEO),



Figure 9.21: NiH2 construction (Thaller & Zimmerman).

- The pressure vessel is required to contain the hydrogen produced on discharge.
- The following picture shows a complete battery pack for a 50 A-h, 22-cell assembly,



Figure 9.22: NiH2 battery pack (Patel).

<u>Temperature Effects</u>
The effect of operating temperature on <u>capacity</u> for NiCd and NiH<sub>2</sub> is shown in the following figure,



Figure 9.23: Capacity versus operating temperature for NiCd and NiH<sub>2</sub> batteries (Patel).

and on life, with depth-of-discharge as parameter, in the following two figures,



Figure 9.24: Battery life versus cell temperature with depth-of-discharge as parameter (Patel).

### **Overall Performance Summary**

• A summary of battery performance is shown in the next,



Figure 9.25: Load power versus mass for NiCd and NiH<sub>2</sub> batteries with depth-of-discharge as parameter (Patel).

• In LEO the NiH<sub>2</sub> battery provides a distinct advantage over NiCd, from the higher usable DOD.

• A comparison of battery <u>mass</u> relative to NiCd is shown for various electrochemistry and NiH<sub>2</sub> designs,



IPV - individual pressure vessel, i.e. one per cell

Figrue 9.26: Battery mass relative to NiCd (Patel).

CPV - common pressure vessel, i.e. housing two cells

SPV - single pressure vessel, one housing all cells

DPV - dependent pressure vessel, each cell has own pressure vessel but with thin walls and flat sides.

• The final table lists life and cost for various battery types,

Table 9.5: Battery	life and rel	ative cost	(Pate	l).

Electo- chemistry	Cycle life in full discharge cycles at 25°C	Calendar life, in years	Self-discharge (percent/month at 25°C)	Relative cost (\$/kWh)
NiCd	1000-2000	10-15	20-30	1500
NiH <sub>2</sub>	2000-4000	10-15	20-30	1500
NiMH	1000-2000	8-10	20-30	2000
Li-ion	500-1000°	а	5-10	3000
Lithium- polymer	500-1000 <sup>a</sup>	a	1–2	>3000

<sup>a</sup>Under development.

• The 4<sup>th</sup> column lists battery self-discharge in percent per month.

A battery will effectively lose its charge without being discharged through a load.

This effect is often experienced in a car battery when the car sits unused for a long period of time.

# 4. Fuel Cells

• The <u>fuel cell</u> is a device that directly and continuously converts chemical energy of a fuel and oxidant to electrical energy in the form of direct current (DC).

•The fuel & oxidant, typically gases, flow <u>continuously</u> into the cell from outside, e.g. storage tanks.

- •The process within the fuel cell occurs at <u>constant pressure</u> (isobaric) and <u>temperature</u> (isothermal).
- Similar to a battery cell, reactions occur at a cathode (+ terminal) and anode (- terminal) that produce a flow of electrons. The process is illustrated generally in the following figure,



Figure 9.27: Fuel-cell schematic (Decher).

• In general, the reactants *A* and *B* combine to form the product *AB* in the <u>electrolyte</u>, where the reactions are:

Cathode (+)	$B + e^- \rightarrow B^-$
Anode (-)	$A - e^- \rightarrow A^+$

Here,  $A^+$  and  $B^-$  are ions that migrate in the electrolyte.

•In a fuel cell, one of the ions is much <u>more mobile</u> than the other and migrates to the side where the less mobile ion is created.

• A measure of current production of a reaction is the <u>Faraday</u> expressed as coulombs per unit molecular mass and is,

$$F = 9.6493 \times 10^7 \text{ C/kg}_{\text{mole}}$$
(9.4.1)

where

C denotes coulombs (<u>not</u> degrees Celsius)

In more practical terms, the capacity density of a substance can be determined by,

	$C_d = n F/\mathfrak{M} \times 1 \text{ A/coulomb/s} \times 1 \text{ hr/3600 s} \text{ A-h/kg}$	(9.4.2)
where	n = valence change or number of electrons involved in reaction	
	$\mathfrak{M} = $ molecular mass, kg/kg <sub>mole</sub>	

• Some cell substance <u>capacity densities</u> are listed in the following table, Table 9.6: Fuel-cell capacitance densities (Decher).

Anode materials	Capacity (Ah/kg)	Cathode materials	Capacity (Ah/kg)
H <sub>2</sub>	26,591	O <sub>2</sub>	3,351
HĈ	11,440	C,H,NO,	1870
Be	5900	F, 1	1408
Li	3850	CÎ,	755
Zn	818	HgO	246
Pb <sup>2+</sup>	257	Ag Cl	185
		Hg Cl	196

#### **Cell Potential or Voltage**

Note: Voltage is the potential energy of electrons, i.e. 1 V = 1 W/A = 1 J/s / coulomb/s = 1 J/coulomb.

• The maximum voltage obtainable (at open circuit) from a cell reaction, per mole of reactant, is given by,

$$V_{oc} = E^o = -\frac{\Delta g \mathfrak{M}}{nF}$$
(9.4.3)

(9.4.4)

where

 $\Delta g$  = the change in the <u>Gibbs energy</u> for the reaction at <u>isobaric</u> and <u>isothermal</u> conditions, J/kg

• The Gibbs energy, or more correctly, free energy, is by definition, on a per unit mass basis,  $g \equiv h - Ts$ 

h = enthalpy, J/kg

where

$$s =$$
entropy, J/kg·K  
• The change in the Gibbs energy is the important quantity in a chemical reaction, i.e.  
 $dg = dh - Tds - sdT$ 

· For a chemical process that undergoes reaction at constant pressure, i.e. p = const (isobaric) and constant temperature, i.e. T = const (isothermal, dT = 0), from an initial state 1 to a final state 2, the Gibbs free energy is,

$$\int_{1}^{2} dg = \int_{1}^{2} dh - \int_{1}^{2} T ds$$

$$\Delta g = \Delta h - T \Delta s \qquad (9.4.5)$$

or

where

 $\Delta h$  = heat from the reaction, can be positive (exothermic) or negative (endothermic)  $\Delta s =$  change in entropy of the reaction.

• The table below gives values of the valence change, n, the open-circuit voltage, E<sup>o</sup>, and the sensitivity to temperature, dE<sup>o</sup>/dT, at 298 K, for several common reactions,

	React	ion	n	E⁰ (V)	d E% d T (mV/K)
H <sub>2</sub> + 0.5 O <sub>2</sub>	→	H-O (I)	2	1.23	-0.85
$H_2 + 0.5 O_2$	$\rightarrow$	H <sub>2</sub> O (g)	2	1.19	-0.23
C + 0.5 O <sub>2</sub>	$\rightarrow$	CO (g)	2	0.71	+0.47
C + O <sub>2</sub>	$\rightarrow$	CO <sub>2</sub> (g)	4	1.02	+0.01
CO + 0.5 O <sub>2</sub>	$\rightarrow$	CO <sub>2</sub> (g)	2	1.33	-0.45
$CH_4 + 2O_2$	$\rightarrow \alpha$	O <sub>2</sub> + 2 H <sub>2</sub> O	8	1.06	43
CH <sub>3</sub> OH + 1.5 O <sub>2</sub>	$\rightarrow cc$	O <sub>2</sub> + 2 H <sub>2</sub> O	6	1.21	
$C_2H_6 + 3.5 O_2$	$\rightarrow 2$	CO <sub>2</sub> + 3 H <sub>2</sub> O	14	1.09	
C <sub>2</sub> H <sub>5</sub> OH + 3 O <sub>2</sub>	$\rightarrow 2$	CO <sub>2</sub> + 3 H <sub>2</sub> O	12	1.14	1
$NH_3 + 0.75 O_2$	$\rightarrow$ .5	$N_2 + 1.5 H_2O$	3	1.17	

Table 9.7: Fuel-cell reactions and open-circuit voltage (Decher).

• A common type of fuel cell, in use on the Space Shuttle, is the hydrogen-oxygen cell where the electrolyte is potassium hydroxide and water.

• This type of cell is shown <u>schematically</u> in the following diagram,



Figure 9.28: Potassium hydroxide hydrogen-oxygen fuel cell (Decher).

• In this cell, the reactions are:

· <u>Cathode</u>:

1) Catalytic reaction of cathode with diatomic oxygen causes it to dissociate and become adsorbed,

$$\frac{1}{2}O_2 \xrightarrow{cat} \frac{1}{2}O + O = O \tag{9.4.6a}$$

2) Atomic oxygen reacts with water, picks up two electrons from cathode, forms the hydroxide ion,  $O+H_2O+2e^- \rightarrow 2OH^-$  (9.4.6b)

3) The hydroxide ion migrates thru the electrolyte to anode. Note: Hydroxide also termed hydroxyl.

4) The overall reaction is,

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$$
 (9.4.6c)

•<u>Anode</u>:

1) Catalytic reaction of anode with diatomic hydrogen causes it to dissociate and become adsorbed,

$$H_2 \xrightarrow{cat} H + H \tag{9.4.7a}$$

2) Atomic hydrogen reacts with hydroxide ions,  $OH^-$ , to form water,

$$2H + 2OH^- \rightarrow 2H_2O + 2e^- \tag{9.4.7b}$$

3) The electrons are transferred by the metallic anode.

4) The overall reaction is,

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^- \tag{9.4.7c}$$

#### •<u>Electrolyte</u>:

1) Potassium hydroxide in the aqueous solution dissociates into potassium and hydroxide ions,

$$KOH \to K^+ + OH^- \tag{9.4.8}$$

2) The positive potassium ion does <u>not</u> participate in the charge (electron) transfer.

3) The negative electrolyte ion facilitates the <u>rapid transfer</u> of charge (electrons).

# Chapter 9

• The <u>overall</u> reaction of a hydrogen-oxygen fuel cell is production of water, i.e.

$$2H_2 + O_2 \rightarrow 2H_2O$$

(9.4.9)

to produce an <u>ideal</u> chemical potential of about 1.23 V.

- As a considerable amount of water is produced, i.e. 1 mole per mole of oxygen, it has to be removed.
- Materials:
  - · Anode: Platinum, palladium, nickel
  - · Cathode: Platinum
  - The electrodes, i.e. anode & cathode, function as chemical catalysts and are therefore termed *electrocatalysts*.
- <u>Actual</u> cell performance produces an open-circuit voltage less than ideal, typically 0.8 to 1.1 V.
- The characteristic <u>V-I curve</u> for a fuel cell is given in the following figure,



Figure 9.29: Typical fuel-cell voltage-current characteristic (Patel).

•The characteristic curve is dominated by three physical phenomenon:

- 1) Activation polarization: The potential expended for fuel and oxidant to undergo reaction at the electrodes.
- 2) Ohmic polarization: The internal electrical resistance of the electrodes, electrolytes, contacts as current is drawn on the cell.
- 3) Concentration polarization: The accumulation of ions & reaction products and depletion of ions and reactants in the electrolyte near electrode surfaces.
- The <u>useful</u> operating range of the cell is in the ohmic polarization region as shown in the following figure of <u>voltage vs current flux</u> (or current density), with service <u>time</u> as parameter,



Figure 9.30: Fuel-cell operating degradation in time (Patel).

 $V = V_{ocl} - kI_d$ 

•The operational cell voltage is typically given as the linear relation,

(9.4.10)

where

 $V_{acl}$  = open-circuit voltage (assuming linear relation to zero current)

k = a constant that varies in time, i.e. k = f t

- $I_d$  = current density, A/m<sup>2</sup>
- From this last relation, the cell <u>power density</u>,  $P_d$ , output at any operating point is,

$$P_d = VI_d = V_{ocl} - kI_d \quad V_{ocl} - V /k$$

The point of <u>maximum</u> power density is the point where  $dP_d/dI_d = 0$ , or,

$$\frac{dP_d}{dI_d} = \frac{1}{k} \left( -kV_{ocl} - V_{ocl} \frac{dV}{dI_d} + k \frac{dP_d}{dI_d} \right)$$
  
and  
$$\frac{dV}{dI_d} = \frac{1}{I} \frac{dP_d}{dI_d} - \frac{P_d}{I_d^2}$$
  
that reduces to, at max power density,  
$$I_d = \frac{1}{2} V_{ocl} / k$$
(9.4.11)

and

$$V = \frac{1}{2}V_{ocl} \tag{9.4.12}$$

$$P_{\max d} = \frac{1}{4} V_{ocl}^2 / k$$
(9.4.13)

• The constant, k, is obtained from a linear fit of the cell  $V-I_d$  curve, i.e. the linear portion of the curve.  $\rightarrow$  Comparable to internal resistance,  $R_i$ .

- From the figure at the bottom of the previous page, the operating voltage, and open-circuit voltage, drop in time as the fuel cell ages  $\rightarrow P_{\text{max}}$  also drops.
  - End-of-life (EOL) is typically considered the point where  $P_{\text{max}}$  drops to load power,  $P_L$ , as shown below,



Figure 9.31: Fuel-cell power degradation in time (Patel).

- In this figure,  $P_{rated}$  corresponds to load power,  $P_L$ .
- For  $P_{\text{max}}/P_{\text{rated}} \leq 1$ , the cell is no longer capable of meeting load requirements.

#### • As voltage is a function of the chemistry:

•Overall operating or <u>bus voltage</u> is achieved by stacking cells in <u>series</u>, i.e.

$$N_{cells} = \frac{V_{bus}}{V_{cell}} \tag{4.14}$$

• The fuel cell is characterized by current density,  $I_d$ , amps/unit area [A/m<sup>2</sup>], so current is proportional to cell area,  $A_{cell}$ , where,

$$I_d = I_L / A_{cell}$$
 or  $A_{cell} = \frac{I_L}{I_d} = \frac{I_L V_L}{I_d V_L} = \frac{P_L}{I_d V_L}$  (4.15)

• Unlike a PV cell, fuel cells are <u>not</u> operated at the max power point, but rather at the point of maximum <u>fuel or thermal efficiency</u>, until near end-of-life.

#### **Cell Efficiency**

• The <u>overall efficiency</u> accounts for all physical mechanisms that reduce the ideal <u>power</u> production of a cell and can be expressed as,

$$\eta_{OA} \equiv \frac{\text{terminal power out}}{\text{chemical power input}} = \frac{VI}{-\dot{m}\Delta h} = \frac{VI}{V_{ioc}I_{id}} = \frac{V_{oc}}{V_{ioc}} \cdot \frac{V}{V_{oc}} \cdot \frac{I}{I_m} = \eta_{th}\eta_V\eta_F$$
(4.16)  

$$I = \text{cell current at the output terminals, A}$$

where

V = cell voltage at the output terminals, V or J/coulomb  $\dot{m}_{fo} = \text{fuel \& oxidant flow rate = product flow rate, kg/s}$   $\Delta h = \text{enthalpy of reaction, J/kg, (usually negative)}$   $V_{ioc} = -\Delta h\mathfrak{M} / nF = \underline{\text{ideal}} \text{ open-circuit voltage (not achievable)}$ (4.17)  $V_{oc} = -\Delta g\mathfrak{M} / nF = \text{open-circuit voltage based on Gibbs energy (achievable)}$ (4.3)  $I_m = \text{maximum current based on fuel \& oxidant flow, i.e. no losses.}$ 

• The <u>maximum thermal efficiency</u>,  $\eta_{th}$ , is the same as the  $\eta_{id}$  defined on page 6-2a,

$$n_{th} \equiv \frac{\text{useable heat}}{\text{heat produced}} = \frac{\Delta g}{\Delta h} = \frac{\Delta g \mathfrak{M} / nF}{\Delta h \mathfrak{M} / nF} = \frac{V_{oc}}{V_{ioc}}$$
(4.18)

where  $\Delta h - \Delta g = T \Delta s$  = the <u>irreversible</u> energy or heat lost in the chemical process that is <u>not</u> usable.

• The voltage efficiency, 
$$\eta_V$$
, is defined,  $\eta_V \equiv \frac{V}{V_{oc}}$  (4.19)

and is a measure of <u>actual</u> operating voltage, V, to <u>achievable</u> open-circuit voltage,  $V_{oc}$ , based on  $\Delta g$ .

• The <u>Faradaic efficiency</u>,  $\eta_F$ , is defined,

$$\eta_F \equiv \frac{\text{actual current produced}}{\text{ideal current based on fuel-oxidant flow}} = \frac{I}{I_m}$$
(4.20)

and is a measure of <u>actual</u> current produced compared to the ideal <u>achievable</u>, i.e.,  $\eta_F < 1$ .

#### **Chapter 9**

• The <u>maximum</u> current that can be produced from the reaction of a fuel & oxidant flow is,

$$I_m = nF\dot{N}_{fo} = nF \ \dot{m}_{fo} / \mathfrak{M} \quad [A]$$
(4.21)

where  $\dot{N}_{fo} = \dot{m}_{fo} / \mathfrak{M}$ , the molar flow rate,  $kg_{mole} / s$ Note: Units check on  $\left[ nF \ \dot{m}_{fo} / \mathfrak{M} \right]$ :  $\left[ \text{ coulombs/kg}_{mole} \ kg/s \ / \ kg/kg_{mole} \right] = \text{ coulombs/s} = \text{ amps}$ • The <u>actual</u> current produced in a cell is,

$$I = \eta_F I_m = \eta_F n F \dot{m}_{fo} / \mathfrak{M} \tag{4.21a}$$

• The <u>required flow rate</u> to produce a load power,  $P_L$ , at a given load voltage,  $V_L$ , is, from (4.21a),

$$\dot{m}_{fo} = \frac{I_L \mathfrak{M}}{\eta_F nF} = \frac{I_L \mathfrak{M}}{\eta_F nF} \cdot \frac{V_L}{V_L} = \frac{P_L \mathfrak{M}}{\eta_F nF V_L}$$
(4.22)

$$\eta_F = \frac{I_L \mathfrak{M}/nF}{\dot{m}_{fo}} = \frac{\text{mass flow of fuel \& oxidant that reacts}}{\text{mass flow of fuel \& oxidant input to cell}}$$
(4.23)

or,

So  $\eta_F$  is a measure of <u>fuel & oxidant utilization</u> and is often termed the *fuel-utilization factor*.

• The various fuel-cell efficiencies are illustrated in the following figure,



Figure 9.32: Fuel-cell efficiency and useful power region (ME Handbook).

In this figure:  $E_{th}$  = the ideal voltage based on total chemical input energy,  $\Delta H$ , J/kg<sub>mole</sub>

 $E^{o}$  = the voltage based on <u>usable</u> chemical input energy,  $\Delta G$ , J/kg<sub>mole</sub>

OCV =actual, achievable open-circuit voltage

 $V_{fc}$  = actual cell <u>operating</u> voltage

 $i_{\text{limiting}}$  = maximum possible current density or <u>short-circuit</u> current density

 $P_{e}$  = actual power or load power

• The linearization of the voltage relation in (6.10) is illustrated in the following  $V-I_d$  plot,



Figure 9.33: Linearization of the fuel-cell voltage-current relation (Decher).

- In this figure: **ideal cell voltage** comparable to  $E^o$  in the figure above **rest voltage** – open-circuit voltage comparable to *OCV* above **resistance voltage drop** – from internal resistance,  $R_i$  or k in (6.10) **activation overvoltage** – voltage drop required for reaction activation **kinetic overvoltage** – voltage drop from high current production
- The following table is a listing of various <u>fuel-cell types</u> and characteristics, Table 9.8: Fuel-cell advantages and drawbacks by type (Decher).

Electrolyte	Temperature (°C)	Advantages	Drawbacks	Status (1994)
Alkaline	70-200	high curent and power density; high efficiency	CO <sub>2</sub> intolerance	Extensive field testing
Proton exchange membrane*	80-110	high current and power density; long operating life	CO intolerance water management; noble metal catalyst	Field testing (automotive)
Phosphoric acid	150-210	well advanced	efficiency; lifetime; noble metal catalyst	Commercially available
Molten carbonate	550-650	high efficiency internal fuel processing, high- grade waste heat	electrolyte in- stability; lifetime	Field testing (2 MW scale)
Solid oxide ceramic	1000-1100	internal fuel processing; high- grade waste heat; lifetime; potentiall inexpensive	high temperature; efficiency; low ionic conductiv y	Laboratory testing (kW scale) ity

\* The proton exchange membrane (PEM) fuel cell uses solid material as a proton conductor in a way that is similar to an acid electrolyte cell. It was initially used in the aerospace industry but developments have led to its strong candidacy for automotive applications; Refs. 7-11 and 7-12.

• The PEM (proton-exchange membrane) fuel cell has a <u>solid polymer</u> electrolyte that allows mobility of positive ions only,



Figure 9.34: The proton-exchange membrane fuel cell (www.fueleconomy.gov).

- For the hydrogen-oxygen, allows only the <u>positive hydrogen ions</u>,  $H^+$ , to pass from anode to cathode.
- · Electrons restricted to flow in external circuit.

#### **Temperature Effect**

• Effect of cell <u>operating temperature</u> on maximum <u>open-circuit voltage</u> (6.3) and <u>thermal efficiency</u> (6.18) is shown in the following table for the  $H_2$ - $O_2$  fuel cell,

Form of water product	Temp °C	$\Delta \overline{g}_f,$ kJ mol <sup>-1</sup> r3/k <sub>2</sub> vol	Max EMF V	Efficiency limit %
Liquid	25	-237.2	1.23	83
Liquid	80	-228.2	1.18	80
Gas	100	-225.2	1.17	79
Gas	200	-220.4	1.14	77
Gas	400	-210.3	1.09	74
Gas	600	-199.6	1.04	70
Gas	800	-188.6	0.98	66
Gas	1000	-177.4	0.92	62

Table 9.9: Effect of operating temperature for H2-O2 fuel cells (Larminie & Dicks).

• Both voltage and efficiency  $\downarrow$  as cell temperature  $\uparrow$ .

• The <u>thermal efficiency</u> in the table is plotted against operating temperature in the following figure. Also shown in the figure is the Carnot efficiency  $(T_h - T_c / T_h)$  of a heat engine where  $T_c = 50^{\circ}$ C,



Figure 9.35: H2-O2 fuel cell thermal efficiency as a function of operating temperature (Larminie & Dicks).

- Although the table and graph suggest lower operating temperatures advantageous, <u>actual voltage</u> in the linear (practical) operating range are <u>higher</u> at higher temperatures.
- The waste heat from a higher-operating-temperature cell could be used, especially in a ground-power application.

# **Pressure Effect**

• It can be shown, from the Nernst equation, that open-circuit voltage varies with operating pressure by the relation,

$$V_{oc} - V_{ref} = \Delta V_{oc} = \frac{\Re T_{op}}{nF} \ln \left( \frac{p_{op}}{p_{ref}} \right) \qquad p_{ref} = \operatorname{atm} \approx 0.1 \text{ MPa}$$
(4.24)

 $T_{op}$ ,  $p_{op}$  – operating temperature, pressure

#### **Actual Operating Voltage**

• On the following page, *V*-*I*<sub>d</sub> curves are given for H<sub>2</sub>-O<sub>2</sub> fuel cells at two different operating temperatures.



Figure 9.36a: Voltage-current characteristic for typical fuel cell at 70 °C operating temperature (Larminie & Dicks). • 800 °C,



Figure 9.36b: Voltage-current characteristic for typical fuel cell at 800 °C operating temperature (Larminie & Dicks).

- Some observations:
  - The theoretical <u>maximum</u> or 'no loss' voltage is <u>higher</u> at <u>lower</u> operating temperature.
  - The  $\Delta$  between <u>actual</u> open-circuit voltage and theoretical max is <u>less</u> at <u>higher</u> operating temp.
  - Less fall in <u>actual operating</u> voltage with  $I_d$ , in the linear range, at <u>higher</u> operating temp.
  - <u>Net effect</u>: <u>actual operating</u> voltage <u>higher</u> at higher operating temp.

# Losses

- The actual operating voltage is degraded by several physical effects:
  - <u>Activation loss</u>: A portion of the voltage is required to drive the chemical reactions at the electrodes.
  - <u>Fuel crossover</u>: Some fuel passes through electrolyte & combines with oxidant no electricity produced.
  - <u>Resistance loss</u>: Voltage loss in the internal resistance of electrodes and electrolyte.
  - · Mass transport: Loss of concentration at electrode surfaces from insufficient flow of fuel & oxidant.

# The Solid Oxide Cell

• The <u>solid-oxide fuel cell</u> (SOFC) is a solid-state device with an oxide-ion-conducting <u>ceramic</u> <u>electrolyte</u>.

- · Allows high operating temperatures.
- · Does <u>not</u> require precious-metal, e.g. platinum, electro-catalysts for the electrodes.



Oxygen, usually from the air

Figure 9.37: The solid-oxide fuel cell (Larminie & Dicks).

- Electrolyte of zirconia and small percentage of yttria  $(Y_2O_3)$
- Above 800 °C, zirconia is a conductor of oxygen ions ( $O^{2^{-}}$ )
- Operate between 800 and 1100 °C.

· High operating temperature presents design challenges, especially for spacecraft use.

# **Fuel Cell Types**

• Tables of fuel cell types listing: mobile ion, operating temperature, application, specific power, life, Table 9.10: Mobile ion, operating temperature range and applications for various fuel-cell types (Larminie & Dicks).

Fuel cell type	Mobile ion	Operating temperature	Applications and notes
Alkaline (AFC)	OH-	50−200°C	Used in space vehicles, e.g. Apollo, Shuttle.
Proton exchange membrane (PEMFC)	$H^+$	30-100°C	Vehicles and mobile applications, and for lower power CHP systems
Direct methanol (DMFC)	$\mathbf{H}^+$	20-90°C	Suitable for portable electronic systems of low power, running for long times
Phosphoric acid (PAFC)	$\mathbf{H}^+$	~220°C	Large numbers of 200-kW CHP systems in use.
Molten carbonate (MCFC)	CO32-	~650°C	Suitable for medium- to large-scale CHP systems, up to MW capacity
Solid oxide (SOFC)	O <sup>2-</sup>	500-1000°C	Suitable for all sizes of CHP systems, 2 kW to multi-MW.

Fuel cell technology	Specific power (W/kg)	Life, in hours
Alkaline	100-150	~ 50,000
Solid polymer	100-150	$\sim 50,000$
Alkaline (space shuttle)	300-400	3000-5000
Lightweight cell under development	600-700	TBD

Table 9.11: Specific-power range and life for various fuel-cell types (Larminie & Dicks).

# **Regenerative Fuel Cell**

- Based on principle of reverse fuel-cell: hydrogen and oxygen are produced from electrolysis of water.
   In <u>reality</u>, requires <u>different</u> electrolyte to crack water by electrolysis, so fuel cell cannot be used as such.
- Concept for spacecraft is shown in following diagram,



PPT – peak power tracking PDU – power distribution unit Figure 9.38: Regenerative-fuel-cell diagram for spacecraft application (Patel).

- Electrolyzer stack is for water electrolysis,  $H_2O \rightarrow H_2 + \frac{1}{2}O_2$
- Power from solar array drives Electrolyzer stack
- •Fuel cell of PEM type
- · System more complicated: additional pumps, plumbing, water storage required
- ·Could be advantageous for high-power missions; proposed for human colonies on Moon, Mars
- <u>System studies</u> show reasonable <u>energy efficiency</u> compared to batteries, and a possible <u>mass advantage</u> for LEO & MEO missions, as shown in the following table and figure that compare a regenerative fuel cell (RFC) to nickel-cadmium and nickel-hydrogen batteries,

Table 9.12: Comparison of battery and regenerative-fuel-cell efficiencies

Energy technology	Round trip energy efficiency		
Nickel cadmium battery	7080		
Nickel hydrogen battery	75-85		
Hydrogen–oxygen RFC:	,		
Mass optimized design	55-60		
Efficiency optimized design	65–70		



Figure 9.39: Mass of battery and regenerative-fuel-cell systems (Patel). • For the RFC:  $t_{dis} = t_{chre}$ , a 50% duty cycle.

#### 5. Radioisotope-Thermoelectric Generators (RTGs)

- The <u>radioisotope thermoelectric generator</u> (RTG) directly converts the high-energy particle-radiation from <u>radioactive</u> decay of an <u>isotope</u> to electrical energy in a <u>semiconductor</u> material:
  - Isotope  $\rightarrow$  <u>Plutonium</u> (Pu) 238,
  - Semiconductor  $\rightarrow$  <u>Silicon-Germanium</u> (Si-Ge)
- Returning to the figure on p. 9-1, the combination of <u>radioisotope-thermoelectric</u> (TE) is most suitable to provide relatively <u>low levels</u> of electrical <u>power</u>, generally < 1 kW, for <u>long durations</u>.
- The technology has been successfully <u>deployed</u> on a <u>number</u> of space missions, primarily for planetary exploration, as listed in the following table,

Table 9.13: Missions employing radio-isotope generators (Brown).

RTG	Spacecraft	Isotope	Power, W	Mass, kg	Power density, W/kg	Life	Status
SNAP-1		Ce-144	500	272.0	1.84	60 d	Cancelled '58
SNAP-1A		Ce-144	125	79.0	1.58	1 y	Cancelled '59
SNAP 3	Nav Sat	Pu-238	2.7	2.1	1.29	5 y	2 flew '61
SNAP-9A	Nav Sat	Pu-238	25	12.2	2.04	6 y	3 flew '63
SNAP-19	Nimbus	Pu-238	30	13.6	2.21	5 y	2 flew '69
SNAP-19	Pioneer	Pu-238	30	13.6	2.21	5 y	1 flew '72
SNAP-19	Viking	Pu-238	40	15.9	2.52	5 y	4 flew '76
SNAP-27	Apollo LSEP	Pu-238	60	20.9	2.87	3 y	5 flew
SNAP-29		Po-210	400	181.0	2.21	90 d	Cancelled '69
MHW	Lincoln Labs	Pu-238	150	36.2	4.14	5 y	1 flew '76
MHW	Voyager	Pu-238	160	37.6	4.25	12 y	6 flew '78
MHW	Galileo	Pu-238	298	55.7	5.35	12 y	2 flew '89
GPHS	Cassini	Pu-238	296	60.0	4.93		2 flew '97

<sup>a</sup>Data, in part, courtesy of C. D. Cochran, U.S. Air Force, Ref. 12, pp. 4-11.

• Maximum achievable power  $\simeq 300$  W.

• Power density steadily increasing to a maximum of 5.35 W/kg.

• A cross-sectional view of the Cassini (Saturn) RTG is shown in the following diagram,



Figure 9.40: Cross-sectional diagram of the Cassini RTG (Brown).

• The *I-V* and *P-V* curves for one of the units on the <u>Viking SNAP-19</u>, the Mars Lander, is shown in the following figure. EOL is for a 5-year mission:



Figure 9.41: Current-voltage characteristic if RTGs (Brown).

- The <u>short-circuit</u> current  $\approx$  21 A at beginning-of-life (BOL).
- Maximum power point  $\simeq$  4.2 V.
- Maximum power  $\simeq$  43 W at BOL.
- Max power-point shifts to  $\simeq 3.8$  V at end-of-life (EOL).
- Max EOL power  $\simeq$  38 W.

#### **Isotopes**

• The following table lists <u>isotopes</u> commonly used in RTGs, their half-life, specific power (W/g) and radiation level (Curies/W),

Isotope	Half-life (years)	Thermal power radiated per gram of isotope (W/g)	Radiation level (Curies/W)
Curium-242	0.45	~100	27
Strontium-90	28	~0.25	153
Plutonium-238	86	~0.55	30

Table 9.14: Thermal power and radiation level of three isotopes (Patel).

• Definition of the Curie:  $1 \text{ Ci} = 3.7 \times 10^{10} \text{ decays per second}$ 

• Note: Plutonium costs ~  $$2x10^6$  per kg

• The mass of the isotope decays exponentially in time,

$$m t \propto 1/e^t$$

and the energy per-unit-time, or power, P, is proportional to the mass and is given by,

(9.5.1)

where

$$P \ t = P_o / e^{0.693t/t_{hl}}$$

$$P_o = \text{power emitted at beginning-of-life}, t = 0, W$$

$$t_{hl} = \text{half-life}$$
Note: For  $t = t_{hl}$ ,  $e^{0.693t/t_{hl}} = e^{0.693} = 2$  and  $P \ t_{hl} = \frac{1}{2}P_o$ 

#### **Thermoelectric Generator**

• The thermoelectric generator is shown schematically in the following diagram,



• Each leg is of a different type of semiconductor material, one <u>p-type</u> and the other, <u>n-type</u>. Figure 9.42: Schematic diagram and electrical model for an RTG (Patel).

• The dissimilar materials are held at a temperature difference,

$$\Delta T = T_{hot} - T_{cold}$$

An <u>electrical potential</u> (open-circuit voltage) results from the <u>Seebeck effect</u> given by,

ge) results from the Seebeck e  
$$V_{oc} = \alpha_{np} \Delta T$$

(9.5.2)

and

$$\alpha_{np} = \alpha_p - \alpha_n \tag{9.5.3}$$

where  $\alpha_{np}$  = the Seebeck coefficient for the n,p material <u>combination</u>, V/K.

- The Seebeck coefficient is considered <u>positive</u> for current flow in the p-type material from  $T_{hot}$  to  $T_{cold}$ .
  - Seebeck coefficients at 373 K (100°C) for two common semiconductors and two metals are,

Material	<u>α, μV/K</u>
Ge	+375.0
Si	-455.0
Fe	+13.6
Pt	-5.2
	0.25

#### **Chapter 9**

• A figure-of-merit, Z, of a thermoelectric material is defined as,

$$Z \equiv \frac{\alpha_i^2}{\rho_R k} \quad \left[\frac{1}{K}\right] \text{ (units: inverse temperature)} \tag{9.5.4}$$

where

 $\alpha_i$  = the Seebeck coefficient for a single material (prior table)

 $\rho_R = \text{resistivity, ohm-m or } J \cdot s \cdot m/\text{coul}^2$ 

k = thermal conductivity, W/K·m

The figure-of-merit for both materials in a couple is given by,

$$Z_{np} = \frac{\alpha_{np}^{2}}{\sqrt{\rho_{Rn}k_{n}} + \sqrt{\rho_{Rp}k_{p}}^{2}}$$
(9.5.5)

where

 $\rho_{Rn,p}$  = resistivity of the n- or p-type material

 $k_{n,p}$  = thermal conductivity of the n- or p-type material

• For the Si-Ge couple,

$$Z_{np} \simeq 0.001 \tag{9.5.6}$$

• The thermal efficiency is defined as,

$$\eta_{th} \equiv \frac{\text{electrical power out}}{\text{thermal power in}} = \frac{P}{Q_h}$$

From a heat balance, that includes internal joule heating  $(I^2R_i)$  and cooling by the Peltier effect (comparable to the Seebeck effect), the fraction of heat removed from the junction as electrical power is,

$$\eta_{th} = \left(1 - \frac{T_c}{T_h}\right) \left\{ \frac{\sqrt{1 + Z\overline{T}} - 1}{\sqrt{1 + Z\overline{T}} + T_c/T_h} \right\}$$
(9.5.7a)  
$$\overline{T} = \sqrt{T_h + T_c} ? \qquad \overline{T} = \sqrt{T_h T_c} \quad \blacktriangleleft \text{check this}$$
(9.5.7b)

where

V - I R = 0

$$I = V_{oc} - IR_i \tag{5.8}$$

(9.5.7b)

The short-circuit current can be found for V = 0,

$$I_{sc} = \frac{V_{oc}}{R_i} = \frac{\alpha_{np}\Delta T}{R_i}$$
(9.5.9)

or

An RTG I-V curve is, from (7.8), linear. Similar to the analysis for the fuel cell as a linear device, the maximum power,  $P_{mp}$ , for the RTG also occurs where,

$$V_{mp} = \frac{1}{2} V_{oc}$$
 and  $I_{mp} = \frac{1}{2} I_{sc}$   
 $P_{mp} = \frac{1}{4} V_{oc} I_{sc}$  (9.5.10)

or

• The I-V, and  $P-V \& \eta_{th} - V$  curves are illustrated in the following figures,



Figure 9.43: Current-voltage and power-voltage characteristics of RTGs (Patel)

• Typically, two or more n-p couples are <u>stacked</u> in <u>series</u>, in a single-stage multi-couple assembly as shown in the following diagram, to achieve the <u>operating</u> (bus) <u>voltage</u> to meet load requirements as shown in the second diagram,



Figure 9.44: Thermoelectric-generator diagram (Patel)



Figure 9.45: Equivalent circuit and operating point for thermoelectric generators (Patel).

# Temperature Effect & Isotope Depletion

• Semiconductor material properties are <u>functions</u> of <u>temperature</u> and therefore the *I*-*V* curve of a TE convertor shifts with <u>operating temperature</u>,  $\Delta T$ , as shown in the figure on the following page,



Figure 9.46: Normalized current versus voltage with temperature as parameter for RTGs (Patel).

• The *I-V* & *P-V* curves shift as the <u>isotope depletes</u> in power output, but  $V_{mp}$  remains about constant, as shown in the figure on the following page.



Figure 9.47: Power versus voltage degradation in time (Patel).

• The <u>measured</u> power output in time from the <u>Voyager II</u> is listed in the following table, Table 9.15: Power output in time for the Voyager RTG (Patel).

Date	Voyager II power output, (W)	Percent of initial power generation
August 1977 (launch date)	478	100
December 1980	436	91
December 1985	398	83
December 1990	370	77
December 1995	344	72
December 1998	327	68%
(21 years)		(after 21 years)

(Source: Data from Mondt, J.F., Proc. of the 36th IECEC, ASME, 2001, Vol. I, pp. 133-139.)

# RTG Systems

- Design considerations:
  - Units have to be put in series to achieve bus voltage.
  - · Current dependent on cross-sectional area of the semiconductor material.
  - Units of a standard design (area) are put in parallel to achieve load current requirements.
  - Total load power determines amount of isotope required.
  - Heat input not converted to electrical power has to be rejected via radiator.
- The following lists the design parameters for a standard RTG used in various missions,

 Table 9.16: Performance of a standard RTG (Patel)
 Image: Comparison of the standard RTG (Patel)

#### Performance characteristic of the standard RTG in use

- Mission life 5 years
- BOL power 285 W
- · EOL power 255 W (notice the negligible decay over mission life)
- Suitable for space shuttle launch
- RTG module 42 cm diameter × 114 cm long
- Total mass 55 kg
- TE 572 SiGe unicouple in 16 circumferential rows
- Operating voltage 28 to 30 V
- Operating temperature gradient  $\triangle T = 707 \text{ K}$
- Operating temperature: 1273 K hot junction, 566 K cold junction

#### **Chapter 9**

• The following table is a list of <sup>238</sup>Pu RTGs for various missions, where the most recent is listed first.

Number in parentheses indicates number of units on spacecraft:					
		Electrical	Heat	Isotope	RTG
Name	Mission(s)	Power, W	Out, W	Mass, kg	Mass, kg
MMRTG	Mars Science Lab	~110	~2000	~4	<45
GPHS-RTG	Cassini (3), New Horizons (1), Galileo (2), Ulysses (1)	300	4400	7.8	55.5
MHW-RTG	Voyager 1 (3), Voyager 2 (3)	390	7200	~4.5	39
SNAP-19	Viking 1 (2), Viking 2 (2), Pioneer 10 (4), Pioneer 11 (4)	35	525	~1	?
SNAP-27	Apollo 12-17 ALSEP (1)	73	1480	3.8	20

Table 9.17: List of plutonium RTGs for various missions (Web).

• The following table lists goals for current RTG R&D programs,

Table 9.18: Performance goals for RTGs (Patel).

Performance parameter	Preset state of the art RTG capabilities	Goals of the Advanced Radioisotope Power System
System efficiency	6.5%	13-25%
Specific power	5 W/kg	9–10 W/kg
Life	> 20 years	TBD
TEC junction	SiGe	Improved SiGe
Operating temperature	1275 °C to 575 °C	1000 °C to 700 °C
Isotope	Pu-238	Pu-238

#### **References**

- 1. Angrist, S., Direct Energy Conversion, 4th Edition, Allyn & Bacon, 1982, ISBN-13: 978-0205077588.
- 2. Brown, C.D., *Elements of Spacecraft Design*, AIAA Education Series, 2002, ISBN 1-56347-524-3.
- 3. Decher, R., Direct Energy Conversion, Oxford University Press, 1997, ISBN 0-19-509572-3.
- Griffin, M.D. & French, J.R., Space Vehicle Design, Second Edition, AIAA Education Series, 2004, ISBN 1-56347-539-1.
- 5. Hyder, A.K. et al., Spacecraft Power Technologies, Imperial College Press, 2000, ISB 1-86094-117-6.
- Kutz, M., Mechancal Engineers' Handbook, Third Edition, Energy and Power, John Wiley & Sons, 2006, ISBN 978-0-471-44990-4
- Larminie, J. & Dicks, A., *Fuel Cell Systems Explained, Second Edition*, John Wiley & Sons, 2003, ISBN-13: 978-0-470-84857-9.
- 8. O'Hayre, R. et al., Fuel Cell Fundamentals, John Wiley & Sons, Inc., 2006, ISBN-13 978-0-471-74148-0.
- 9. Patel, M.R., Spacecraft Power Systems, CRC Press, 2005, ISBN 0-8493-2786-5.