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).](image)

- **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:**
  - 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.).

<table>
<thead>
<tr>
<th>System or Component</th>
<th>Parameter</th>
<th>Circa 1985</th>
<th>Estimated 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar-Battery Systems</td>
<td>Power Output</td>
<td>5 kW</td>
<td>100 kW</td>
</tr>
<tr>
<td></td>
<td>Specific Power</td>
<td>10 W/kg</td>
<td>50 W/kg</td>
</tr>
<tr>
<td></td>
<td>Solar Array-Battery Costs</td>
<td>$3000/W</td>
<td>$1600/W</td>
</tr>
<tr>
<td>Solar Cells and Arrays</td>
<td>Cell Power Output</td>
<td>5 kW</td>
<td>100 kW</td>
</tr>
<tr>
<td></td>
<td>Cell Efficiency (in space)</td>
<td>14%</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td>Array Specific Power</td>
<td>35 W/kg</td>
<td>150 W/kg</td>
</tr>
<tr>
<td></td>
<td>Array Design Life (LEO/GEO)</td>
<td>5yr/7yr</td>
<td>10yr/15yr</td>
</tr>
<tr>
<td></td>
<td>Array Specific Cost</td>
<td>$1500/W</td>
<td>$500/W</td>
</tr>
</tbody>
</table>

Batteries

Primary

- AgZn Energy Density 150 W-hr/kg Design Life 2 yr
- LiSOCl₂ Energy Density 200 W-hr/kg Design Life 3 yr

Secondary

- NiCd (LEO) Energy Density 10 W-hr/kg Design Life 5 yr/10 yr
- NiCd (GEO) Energy Density 15 W-hr/kg
- NiCd (LEO/GEO) Energy Density 25 W-hr/kg
- NiH₄ (LEO) Energy Density 30 W-hr/kg
- NiH₄ (GEO) Energy Density

Nuclear Power Reactors

- Power Level 10 kW
- Specific Power 10 W/kg
- Efficiency 10%

RTG

- Power Level 2 kW
- Specific Power 6 W/kg
- Efficiency 8%

Typical Overall System Parameters

- Power 12 kW 25 kW
- Voltage 28 V 50 V
- Frequency DC DC/AC
- Cost on-orbit ~$1000/kW-hr
- Radiator Specific Mass 20 kg/kW

Table 9.2: Power Limits & Performance.

<table>
<thead>
<tr>
<th>System</th>
<th>Limit, kW</th>
<th>Eff. %</th>
<th>SP, W/kg</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar-PV</td>
<td>20</td>
<td>15-30</td>
<td>5-10</td>
<td>experience</td>
</tr>
<tr>
<td>RTG</td>
<td>1</td>
<td>7-15</td>
<td>7-15</td>
<td>same</td>
</tr>
<tr>
<td>Nuclear-TEC</td>
<td>100</td>
<td>7-15</td>
<td>?</td>
<td>projected</td>
</tr>
</tbody>
</table>

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,

![Power system block diagram](image)

Figure 9.2: Power system block diagram (Patel).

System Voltage

- Initial spacecraft designed for 28 VDC (automotive typically 12 VDC).
- Higher the power requirement → higher the operating voltage to reduce losses, i.e.
  \[ P = IV \quad V = IR \quad I = \text{current, amperes} \quad R = \text{resistance, ohms} \]
  \[ P_{\text{loss}} = I^2R \quad \text{in conductors} \]
  
  For fixed power: Higher the voltage, lower the current, lower the loss.

- Standard distribution (“bus”) voltages:

![Bus voltage versus power level for several spacecraft](image)

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 arcing above ~180 to 200 V.
2. At 100 V, for every square meter of exposed conductor area, leakage current \( \approx 1 \text{ mA} \).
   
   Leakage current increases with voltage.
3. Above 160 V, conductors require insulation (additional mass).
- **Voltage Scaling Law:**
  Design experience has shown empirically,
  \[ V_{opt} = 0.025 \times P \]  \hspace{1cm} (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,
  \[ m_{new} = m_{exist} \times \left( \frac{P_{new}}{P_{exist}} \right)^{0.7} \]  \hspace{1cm} (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,

![Spacecraft power system block diagram](image)

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 solar-photovoltaic arrays and batteries as shown schematically in the following figure.

![Solar PV - Battery System Diagram](image)

Figure 9.5: Photovoltaic battery system (Patel).

PMAD = power management and distribution
PRU = power regulation unit
BAT = batteries
EPS = electrical power system
\( \alpha = \alpha \) – drive, rotates 360° once per orbit
\( \beta = \beta \) – gimbals, rotate ±β° to compensate for the solar β 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.

![Photovoltaic Cell Cross-Section](image)

Figure 9.6: Photovoltaic cell cross-section (Patel).
The conversion efficiency of a PV cell is given by,

$$\eta = \frac{\text{electrical power output}}{\text{solar power incident on the cell}} = \frac{IV}{P_{SF}}$$  \hspace{1cm} (9.2.1)

Conversion efficiency for three common PV cell materials:
- 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.](image)

- About two-thirds of solar-radiation energy lies between wavelengths, \( \lambda = 0.4 - 1.1 \ \mu m \).
- Silicon has a cut-off wavelength of about, \( \lambda = 1.1 \ \mu m \).
- 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,

$$e_p = h\nu$$  \hspace{1cm} (9.2.2)

where
- \( h = \) Planck's constant = 6.626 \times 10^{-34} \ \text{J-s} \)
- \( \nu = \) frequency, cps

and,

$$\nu = \frac{c}{\lambda}$$  \hspace{1cm} (9.2.3)

where
- \( c = \) speed of light = 2.9979 \times 10^8 \ \text{m/s} \)
- \( \lambda = \) wave length

The complex physics of a PV cell can be represented by the electrical circuit in the following diagram.

![Figure 9.8: Photovoltaic-cell equivalent circuit (Patel).](image)
• The cell acts as a constant current source shunted by a perfect diode:

Here,

\[ I_s = \text{source or photo current} \]
\[ I_d = \text{the diode current} \]
\[ I_{sh} = \text{the ground shunt current} \]
\[ R_i = \text{internal resistance of the material} \]
\[ R_{sh} = \text{resistance to internal current leakage to ground} \]

In an ideal PV cell, \( R_i = 0 \) (no series loss)
\( R_{sh} = \infty \) (no leakage to ground)

In a typical silicon cell, \( R_i = 0.05 \text{ to } 0.10 \, \Omega \)
\( R_{sh} = 200 \text{ to } 300 \, \Omega \)

• 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 open-circuit voltage, \( V_{oc} \), and is the case for zero load current, i.e. an open circuit, given by,

\[ V_{oc} = V + IR_i \tag{9.2.5} \]

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

\[ I_d = I_o \left[ e^{\frac{qV_{oc}}{AKT}} - 1 \right] \tag{9.2.6} \]

where

\[ I_o = \text{diode-saturation (dark) current} \]
\[ q = \text{electron charge} = 0.1592 \times 10^{-18} \, \text{coulombs} \]
\[ k = \text{Boltzmann's constant} = 1.381 \times 10^{-23} \, J/K \]
\[ T = \text{absolute temperature, K} \]
\[ A = \text{curve-fit constant} \]

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

\[ I = I_s - I_o \left[ e^{\frac{qV_{oc}}{AKT}} - 1 \right] \frac{V_{oc}}{R_{sh}} \tag{9.2.7} \]

where \( V_{oc}/R_{sh} = \text{ground leakage and can be ignored compared to } I_s \) & \( I_d \).

• The diode-saturation current is measured by applying an open-circuit voltage, \( V_{oc} \), to the cell in the dark and measuring the current going to the cell.

• Under sunlight, the diode current, \( I_d \), is small compared to \( I_s \).
· 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).](image)

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

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 output power** is the product of load current and voltage. The functional relationship is shown in (b) in the figure at the top.

- The **maximum power** 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:

<table>
<thead>
<tr>
<th>Material</th>
<th>$V_{mp}$, V</th>
<th>$I_{mp}$, mA/cm$^2$</th>
<th>$P_{mp}$, mW/cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>0.50</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.0</td>
<td>30</td>
<td>40</td>
</tr>
</tbody>
</table>

· An important effect for solar-array design is PV-cell degradation from radiation of charged particles in space: Protons, electrons, alpha particles.
- Different particles have different damaging effect on $I_{sc}$ & $V_{oc}$.
Radiation levels measured in MeV ($10^6$ 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.).](image)

### 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 **electrochemical** form and are of two basic types:
  - **Primary** – The electrochemical reaction is irreversible, i.e. cannot be reused after discharge. Applied in short-duration missions, e.g. sounding-rocket payloads.
  - **Rechargeable** – The electrochemical reaction is reversible. Device can be recharged with direct current 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).](image)

- Electrode plates are **positive** and **negative** (negative usually the ground terminal, e.g. auto system).
- The electrode plates separated by electrical insulator.
- Electrolyte fills volume and provides the electrochemical reaction with the electrode plates.
- Cell **voltage** determined by electrochemistry and not on size → 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$^3$ or W-h/l (per liter) \[ 1 \text{ liter} = 1 \times 10^{-3} \text{ m}^3 \]

**Specific power** = power the battery can **practically** deliver per unit mass, W/kg

**Specific density** = power the battery can **practically** 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 **electrochemistry**, compared by energy density vs. specific energy.

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

**Nickel cadmium, NiCd:** Most common type for satellite use up to about the mid-1980s.
- Positive electrode: Nickel impregnated with hydroxide, nickel oxyhydroxide NiOOH
- Negative electrode: Nickel impregnated with cadmium hydroxide (toxic)
- Electrolyte: Potassium hydroxide (KOH)

**Nickel hydrogen, NiH$_2$:** Most widely used type in the last 20 years, replaced NiCds, higher $E_{sp}$
- 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:** High energy density (Li, low atomic mass), wide commercial application
- Positive electrode: LiNiCoO$_2$
- Negative electrode: Mixture of two graphites with non-PVDF binder (?)
- Electrolyte: LiPF$_6$ salt (solid)
Spacecraft Power

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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$_2$ or LiMnO$_4$
Negative electrode: Li or carbon-Li intercalation compound
Electrolyte: Solid polymer, e.g. polyethylene oxide or polyacrylonitrile

- Performance 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).

<table>
<thead>
<tr>
<th>Electrochemistry</th>
<th>Specific energy (Wh/kg)</th>
<th>Energy density (Wh/l)</th>
<th>Specific power (W/kg)</th>
<th>Power density (W/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCd</td>
<td>40-5</td>
<td>50-100</td>
<td>150-200</td>
<td>300-500</td>
</tr>
<tr>
<td>NiH$_2$</td>
<td>45-65</td>
<td>35-50</td>
<td>150-200</td>
<td>200-300</td>
</tr>
<tr>
<td>NiMH</td>
<td>50-70</td>
<td>140-180</td>
<td>150-200</td>
<td>300-500</td>
</tr>
<tr>
<td>Li-ion</td>
<td>90-150</td>
<td>150-250</td>
<td>200-220</td>
<td>400-500</td>
</tr>
<tr>
<td>Lithium-polymer</td>
<td>100-200</td>
<td>150-300</td>
<td>&gt;200</td>
<td>&gt;400</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Electrochemistry</th>
<th>Cut-off voltage</th>
<th>Discharge voltage</th>
<th>Charge terminate voltage</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCd</td>
<td>1.0</td>
<td>1.25</td>
<td>1.55</td>
<td>Exhibits memory effect</td>
</tr>
<tr>
<td>NiH$_2$</td>
<td>1.0</td>
<td>1.25</td>
<td>1.55</td>
<td>No memory effect</td>
</tr>
<tr>
<td>NiMH</td>
<td>1.0</td>
<td>1.25</td>
<td>1.55</td>
<td>Temperature sensitive</td>
</tr>
<tr>
<td>Li-ion</td>
<td>2.7</td>
<td>3.50</td>
<td>4.20</td>
<td>Safe, contains no metallic lithium</td>
</tr>
<tr>
<td>Lithium-polymer</td>
<td>2.7</td>
<td>3.50</td>
<td>4.20</td>
<td>Contains metallic lithium</td>
</tr>
<tr>
<td>Silver-zinc</td>
<td>1.3</td>
<td>1.50</td>
<td>2.05</td>
<td>Needs good air management to limit self-discharge rate</td>
</tr>
</tbody>
</table>

- Cut-off voltage – minimum useful discharge voltage
- Discharge voltage – average voltage during discharge
- Charge terminate voltage – voltage at end of charge cycle

Battery Characteristics
- Cell capacity defined in terms of ampere-hours (Ah) at some reference temperature, e.g. 60°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-discharge as shown in the following plot,
Here, $\text{SOC}$ is state-of-charge,

$$\text{SOC} = \frac{\text{remaining Ah capacity}}{\text{rated Ah capacity}}$$  \hspace{1cm} (9.3.2)

Depth-of-discharge is,

$$\text{DOD} = \frac{\text{Ah extracted from fully charged state}}{\text{rated Ah capacity}}$$  \hspace{1cm} (9.3.3)

From (3.2) & (3.3),

$$\text{DOD} = 1 - \text{SOC}$$  \hspace{1cm} (9.3.4)

The product of voltage and Ah rating gives the energy rating of the battery in Watt-hours,

$$E_r = V \times Ah \quad \text{W-h}$$  \hspace{1cm} (9.3.5)

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

![Cell voltage vs depth-of-discharge](image)

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 → 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:**

$$\left(\frac{C}{D}\right)_R = \frac{\text{ampere-hours input for 100% SOC}}{\text{ampere-hours output}}$$  \hspace{1cm} (9.3.6)

Example) $\frac{C}{D}_R = 1.1$ 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.
- The charge/discharge cycle for a NiH$_2$ battery in LEO in terms of cell voltage vs. time for various levels of DOD (discharge rate) is shown in the following figure,

![Charge-discharge cycle for NiH$_2$ batteries](image)

Figure 9.15: Charge-discharge cycle for NiH$_2$ batteries (Patel).

- Typical charge/discharge cell voltages for NiH$_2$ 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,

![Cycle life versus depth-of-discharge and temperature for NiCd cells](image)

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,

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

Charging efficiency is a function of charge rate and operating temperature as shown in the following figures for NiH$_2$ batteries,
Charge efficiency is a function of charge rate and operating temperature as shown in the following figure for a typical NiCd battery,

- The energy efficiency increases with charging rate.
The equivalent electrical circuit to model a battery is,

\[ \text{Figure 9.18: Battery equivalent circuit (Patel).} \]

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 voltage decreases and internal resistance increases linearly with depth-of-discharge as given by,

\[
\begin{align*}
E_i &= E_{\alpha} - k_V \times \text{DOD} \\
R_i &= R_{\alpha} + k_R \times \text{DOD}
\end{align*}
\]

where

- \( E_{\alpha} \) = voltage in fully charged state
- \( k_V \) = electrochemistry constant for voltage
- \( R_{\alpha} \) = 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 series where the voltage is additive, i.e.

\[
V_B = \sum_i^N V_i \quad \text{and} \quad N = \frac{V_B}{V_i}
\]

where

- \( V_i \) = terminal voltage of individual battery
- \( N \) = number batteries in series to give \( V_B \)

• Battery voltage, \( V_{\text{bat}} \), as a function of current, \( I \), is given by,

\[ V_{\text{bat}} = E_i - IR_i \] (9.3.11)

• Under increasing load, \( P_{\text{load}} \), battery terminal voltage drops, from the current increase,

\[
\begin{align*}
P_{\text{load}} &= I^2 R_L \quad \rightarrow \quad I = \sqrt{P_{\text{load}} / R_L} \\
V_{\text{bat}} &= E_i - R_i \sqrt{P_{\text{load}} / R_L}
\end{align*}
\]

(9.3.12)

• The operating point is the intersection of,

\[ V_{\text{load}} = IR_L \quad \text{and} \quad V_{\text{bat}} = E_i - IR_i \]

as shown in the following figure,
Figure 9.19: Load and battery voltage versus current (Patel).

- The preceding figure shows the intersection of the battery line and load line that gives the operating point, P, for the system.

- Maximum power deliverable to the load is,

\[ P_{\text{max}} = I_{\text{max}}^2 R_L \]  \hspace{1cm} (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,

\[ P_{\text{bat}} = IE_i = I^2 R_i + I^2 R_L = 2I^2 R_i \]

or,

\[ P_{\text{max}} = 2I_{\text{max}}^2 R_i \]  \hspace{1cm} (9.3.14)

so that maximum power, \( P_{\text{max}} \), deliverable to the load, \( I_{\text{max}}^2 R_L \), is 50%, i.e. half of the power is consumed by \( R_i \).

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

\[ E_i = I_{\text{max}} R_i + R_L = 2I_{\text{max}} R_i \]

or,

\[ E_i^2 = 4I_{\text{max}}^2 R_i^2 = 4R_i P_{\text{max}} \]

giving,

\[ P_{\text{max}} = \frac{E_i^2}{4R_i} \]  \hspace{1cm} (9.3.15)

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

- Cell internal resistance 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 NiH₂ cell at 100% state-of-charge (SOC), i.e. fully charged, in the following figure.

Figure 9.20: Cell resistance versus temperature (°C) for NiH₂ batteries (Patel).
Battery Design

- The following diagram shows the construction of a nickel-hydrogen cell for a Comsat (communications satellite in GEO).

![Diagram of NiH2 construction](image)

**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,

![Complete NiH2 battery pack](image)

**Figure 9.22: NiH2 battery pack (Patel).**
**Temperature Effects**

- The effect of operating temperature on capacity for NiCd and NiH$_2$ is shown in the following figure,

![Graph showing capacity versus operating temperature for NiCd and NiH$_2$ batteries](image)

Figure 9.23: Capacity versus operating temperature for NiCd and NiH$_2$ batteries (Patel).

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

![Graph showing battery life versus cell temperature](image)

(a) NiCd battery life

![Graph showing NiH$_2$ battery life](image)

(b) NiH$_2$ battery life

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.

![Battery Performance Graph]

- In LEO the NiH$_2$ battery provides a distinct advantage over NiCd, from the higher usable DOD.

- A comparison of battery mass relative to NiCd is shown for various electrochemistry and NiH$_2$ designs.

![Battery Mass Comparison]

- The final table lists life and cost for various battery types.

<table>
<thead>
<tr>
<th>Electrochemistry</th>
<th>Cycle life in full discharge cycles at 25°C</th>
<th>Calendar life, in years</th>
<th>Self-discharge (percent/month at 25°C)</th>
<th>Relative cost ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCd</td>
<td>1000–2000</td>
<td>10–15</td>
<td>20–30</td>
<td>1500</td>
</tr>
<tr>
<td>NiH$_2$</td>
<td>2000–4000</td>
<td>10–15</td>
<td>20–30</td>
<td>1500</td>
</tr>
<tr>
<td>NiMH</td>
<td>1000–2000</td>
<td>8–10</td>
<td>20–30</td>
<td>2000</td>
</tr>
<tr>
<td>Li-ion</td>
<td>500–1000*</td>
<td>a</td>
<td>5–10</td>
<td>3000</td>
</tr>
<tr>
<td>Lithium-polymer</td>
<td>500–1000*</td>
<td>a</td>
<td>1–2</td>
<td>&gt;3000</td>
</tr>
</tbody>
</table>

*Under development

- The 4th 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 fuel cell 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 continuously into the cell from outside, e.g., storage tanks.
- The process within the fuel cell occurs at constant pressure (isobaric) and temperature (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 electrolyte, 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 more mobile 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 Faraday expressed as coulombs per unit molecular mass and is,

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

(9.4.1)

where $C$ denotes coulombs (not degrees Celsius)

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

$$ C_d = n F / \omega R \times 1 \text{ A/coulomb/s} \times 1 \text{ hr/3600 s} = \text{ A-h/kg} $$

(9.4.2)

where $n =$ valence change or number of electrons involved in reaction

$\omega R =$ molecular mass, kg/kg mole

- Some cell substance capacity densities are listed in the following table,

```
Table 9.6: Fuel-cell capacitance densities (Decher).
<table>
<thead>
<tr>
<th>Anode materials</th>
<th>Capacity (Ah/kg)</th>
<th>Cathode materials</th>
<th>Capacity (Ah/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2$</td>
<td>26.591</td>
<td>$O_2$</td>
<td>3.351</td>
</tr>
<tr>
<td>$H\hat{C}$</td>
<td>11.440</td>
<td>$C_7H_5NO_2$</td>
<td>1870</td>
</tr>
<tr>
<td>Be</td>
<td>5900</td>
<td>$F_2$</td>
<td>1408</td>
</tr>
<tr>
<td>Li</td>
<td>3850</td>
<td>$Cl_2$</td>
<td>755</td>
</tr>
<tr>
<td>Zn</td>
<td>818</td>
<td>$HgO$</td>
<td>246</td>
</tr>
<tr>
<td>Pb\textsuperscript{2+}</td>
<td>257</td>
<td>$Ag Cl$</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Hg Cl$</td>
<td>196</td>
</tr>
</tbody>
</table>
```
Cell Potential or Voltage

Note: Voltage is the potential energy of electrons, i.e. \( 1 \text{ V} = 1 \text{W/A} = 1 \text{ J/s} / \text{coulomb/s} = 1 \text{ J/coulomb.} \)

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

\[
V_{oc} = E^o = \frac{\Delta g_{\text{mol}}}{nF}
\]

where \( \Delta g = \) the change in the Gibbs energy for the reaction at isobaric and isothermal conditions, \( J/\text{kg} \)

- The Gibbs energy, or more correctly, free energy, is by definition, on a per unit mass basis,

\[
g = h - Ts
\]

where

- \( h = \) enthalpy, \( J/\text{kg} \)
- \( s = \) entropy, \( J/\text{kg} \cdot \text{K} \)

- The change in the Gibbs energy is the important quantity in a chemical reaction, i.e.

\[
dg = dh - Tds
\]

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

\[
\int_1^2 dg = \int_1^2 dh - \int_1^2 Tds
\]

or

\[
\Delta g = \Delta h - T\Delta s
\]

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, \( E^o \), and the sensitivity to temperature, \( dE^o/dT \), at 298 K, for several common reactions.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( n )</th>
<th>( E^o ) (V)</th>
<th>( dE^o/dT ) (mV/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{H}_2 + 0.5 \text{O}_2 \rightarrow \text{H}_2\text{O (l)} )</td>
<td>2</td>
<td>1.23</td>
<td>-0.85</td>
</tr>
<tr>
<td>( \text{H}_2 + 0.5 \text{O}_2 \rightarrow \text{H}_2\text{O (g)} )</td>
<td>2</td>
<td>1.19</td>
<td>-0.23</td>
</tr>
<tr>
<td>( \text{C} + 0.5 \text{O}_2 \rightarrow \text{CO (g)} )</td>
<td>2</td>
<td>0.71</td>
<td>+0.47</td>
</tr>
<tr>
<td>( \text{C} + \text{O}_2 \rightarrow \text{CO}_2 (g) )</td>
<td>4</td>
<td>1.02</td>
<td>+0.01</td>
</tr>
<tr>
<td>( \text{CO} + 0.5 \text{O}_2 \rightarrow \text{CO}_2 (g) )</td>
<td>2</td>
<td>1.33</td>
<td>-0.45</td>
</tr>
<tr>
<td>( \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O} )</td>
<td>8</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>( \text{CH}_3\text{OH} + 1.5 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O} )</td>
<td>6</td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_5\text{OH} + 3.5 \text{O}_2 \rightarrow 2 \text{CO}_2 + 3 \text{H}_2\text{O} )</td>
<td>14</td>
<td>1.09</td>
<td></td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_4\text{OH} + 3 \text{O}_2 \rightarrow 2 \text{CO}_2 + 3 \text{H}_2\text{O} )</td>
<td>12</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td>( \text{NH}_3 + 0.75 \text{O}_2 \rightarrow .5 \text{N}_2 + 1.5 \text{H}_2\text{O} )</td>
<td>3</td>
<td>1.17</td>
<td></td>
</tr>
</tbody>
</table>

- 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 schematically in the following diagram,

- **Cathode:**
  1) Catalytic reaction of cathode with diatomic oxygen causes it to dissociate and become adsorbed,
     \[ \frac{1}{2}O_2 \xrightarrow{\text{cat}} \frac{1}{2}O + O = O \]  

    \[ (9.4.6a) \]

  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,
     \[ \frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \]  

    \[ (9.4.6c) \]

- **Anode:**
  1) Catalytic reaction of anode with diatomic hydrogen causes it to dissociate and become adsorbed,
     \[ H_2 \xrightarrow{\text{cat}} H + H \]  

    \[ (9.4.7a) \]

  2) Atomic hydrogen reacts with hydroxide ions, \( OH^- \), to form water,
     \[ 2H + 2OH^- \rightarrow 2H_2O + 2e^- \]  

    \[ (9.4.7b) \]

  3) The electrons are transferred by the metallic anode.

  4) The overall reaction is,
     \[ H_2 + 2OH^- \rightarrow 2H_2O + 2e^- \]  

    \[ (9.4.7c) \]

- **Electrolyte:**
  1) Potassium hydroxide in the aqueous solution dissociates into potassium and hydroxide ions,
     \[ KOH \rightarrow K^+ + OH^- \]  

    \[ (9.4.8) \]

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

  3) The negative electrolyte ion facilitates the rapid transfer of charge (electrons).
The overall reaction of a hydrogen-oxygen fuel cell is production of water, i.e.

$$2H_2 + O_2 \rightarrow 2H_2O$$  \hspace{1cm} (9.4.9)

to produce an ideal chemical potential of about $1.23 \text{ V}$.

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.

Actual cell performance produces an open-circuit voltage less than ideal, typically $0.8$ to $1.1 \text{ V}$.

The characteristic $V-I$ curve for a fuel cell is given in the following figure,

![Figure 9.29: Typical fuel-cell voltage-current characteristic (Patel).](image)

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 useful operating range of the cell is in the ohmic polarization region as shown in the following figure of voltage vs current flux (or current density), with service time as parameter,
• The operational cell voltage is typically given as the linear relation,

\[ V = V_{oc} - kI_d \]  

(9.4.10)

where

\[ V_{oc} = \text{open-circuit voltage (assuming linear relation to zero current)} \]

\[ k = \text{a constant that varies in time, i.e. } k = f(t) \]

\[ I_d = \text{current density, A/m}^2 \]

• From this last relation, the cell power density, \( P_d \), output at any operating point is,

\[ P_d = VI_d = V_{oc} - kI_d \]

\[ V \]

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In this figure, \( P_{\text{rated}} \) corresponds to load power, \( P_L \).

For \( \frac{P_{\text{max}}}{P_{\text{rated}}} \leq 1 \), the cell is no longer capable of meeting load requirements.

- As voltage is a function of the chemistry:
  - Overall operating or bus voltage is achieved by stacking cells in series, i.e.
  
  \[
  N_{\text{cells}} = \frac{V_{\text{bus}}}{V_{\text{cell}}}
  \]
  
  (4.14)

  - The fuel cell is characterized by current density, \( I_d \), amps/unit area \([\text{A/m}^2]\), so current is proportional to cell area, \( A_{\text{cell}} \), where,
  
  \[
  I_d = I_L / A_{\text{cell}} \quad \text{or} \quad A_{\text{cell}} = I_L I_d / V_L = I_d V_L / I_d V_L
  \]
  
  (4.15)

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

### Cell Efficiency

- The **overall efficiency** accounts for all physical mechanisms that reduce the ideal power production of a cell and can be expressed as,

  \[
  \eta_{\text{OA}} = \frac{\text{terminal power output}}{\text{chemical power input}} = \frac{VI}{-m\Delta h} = \frac{VI}{V_{\text{loc}} I_{\text{id}}} = \frac{V_{\text{oc}} V}{V_{\text{oc}} I_m} = \eta_{\text{th}} \eta_{V} \eta_{F}
  \]
  
  (4.16)

  where

  - \( I = \text{cell current at the output terminals, A} \)
  - \( V = \text{cell voltage at the output terminals, V or J/coulomb} \)
  - \( m_{fo} = \text{fuel & oxidant flow rate = product flow rate, kg/s} \)
  - \( \Delta h = \text{enthalpy of reaction, J/kg, (usually negative)} \)
  - \( V_{\text{loc}} = - \frac{\Delta h \mathcal{R}}{nF} = \text{ideal open-circuit voltage (not achievable)} \)
  - \( V_{\text{oc}} = - \frac{\Delta g \mathcal{R}}{nF} = \text{open-circuit voltage based on Gibbs energy (achievable)} \)
  - \( I_m = \text{maximum current based on fuel & oxidant flow, i.e. no losses} \)

- The **maximum thermal efficiency**, \( \eta_{\text{th}} \), is the same as the \( \eta_{id} \) defined on page 6-2a,

  \[
  \eta_{\text{th}} = \frac{\text{useable heat}}{\text{heat produced}} = \frac{\Delta g \mathcal{R}}{\Delta h \mathcal{R}} = \frac{V_{\text{oc}}}{V_{\text{loc}}}
  \]
  
  (4.18)

  where \( \Delta h - \Delta g = T \Delta s = \text{the irreversible energy or heat lost in the chemical process that is not usable} \)

- The **voltage efficiency**, \( \eta_{V} \), is defined,

  \[
  \eta_{V} = \frac{V}{V_{\text{oc}}}
  \]
  
  (4.19)

  and is a measure of actual operating voltage, \( V \), to achievable open-circuit voltage, \( V_{\text{oc}} \), based on \( \Delta g \).

- The **Faradaic efficiency**, \( \eta_{F} \), is defined,

  \[
  \eta_{F} = \frac{\text{actual current produced}}{\text{ideal current based on fuel-oxidant flow}} = \frac{I}{I_m}
  \]
  
  (4.20)

  and is a measure of actual current produced compared to the ideal achievable, i.e., \( \eta_{F} < 1 \)
• The maximum current that can be produced from the reaction of a fuel & oxidant flow is,

$$I_m = nF\dot{N}_{fo} = nF \dot{m}_{fo} / \mathcal{M} \quad [\text{A}]$$

(4.21)

where

$$\dot{N}_{fo} = \dot{m}_{fo} / \mathcal{M}$$, the molar flow rate, kg mole/s

Note: Units check on \(nF \dot{m}_{fo} / \mathcal{M}\) : [coulombs/kg mole \ kgs / \ kgs/kg mole] = coulombs/s = amps

• The actual current produced in a cell is,

$$I = \eta_F I_m = \eta_F nF\dot{m}_{fo} / \mathcal{M}$$

(4.21a)

• The required flow rate to produce a load power, \(P_L\), at a given load voltage, \(V_L\), is, from (4.21a),

$$\dot{m}_{fo} = \frac{I_L \mathcal{M}}{\eta_F nF} = \frac{I_L \mathcal{M}}{\eta_F nF} \frac{V_L}{V_L} = \frac{P_L \mathcal{M}}{\eta_F nF V_L}$$

(4.22)

or,

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

(4.23)

So \(\eta_F\) is a measure of fuel & oxidant utilization 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).](image)

In this figure:

- \(E_{th}\) = the ideal voltage based on total chemical input energy, \(\Delta H\), J/kg mole
- \(E^*\) = the voltage based on usable chemical input energy, \(\Delta G\), J/kg mole
- \(OCV\) = actual, achievable open-circuit voltage
- \(V_{fc}\) = actual cell operating voltage
- \(i_{\text{limiting}}\) = maximum possible current density or short-circuit 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,

![Diagram of $V-I_d$ plot](image)

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

In this figure:
- **ideal cell voltage** – comparable to $E'$ in the figure above
- **rest voltage** – open-circuit voltage comparable to OCV above
- **resistance voltage drop** – from internal resistance, $R$, 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 fuel-cell types and characteristics,

Table 9.8: Fuel-cell advantages and drawbacks by type (Decher).

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>Temperature ($^\circ$C)</th>
<th>Advantages</th>
<th>Drawbacks</th>
<th>Status (1994)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline</td>
<td>70-200</td>
<td>high current and power density; high efficiency</td>
<td>CO$_2$ intolerance</td>
<td>Extensive field testing</td>
</tr>
<tr>
<td>Proton exchange membrane*</td>
<td>80-110</td>
<td>high current and power density; long operating life</td>
<td>CO intolerance; water management; noble metal catalyst</td>
<td>Field testing (automotive)</td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>150-210</td>
<td>well advanced</td>
<td>efficiency; lifetime; noble metal catalyst</td>
<td>Commercially available</td>
</tr>
<tr>
<td>Molten carbonate</td>
<td>550-650</td>
<td>high efficiency</td>
<td>electrolyte instability; lifetime</td>
<td>Field testing (2 MW scale)</td>
</tr>
<tr>
<td>Solid oxide ceramic</td>
<td>1000-1100</td>
<td>internal fuel processing; high-grade waste heat</td>
<td>high temperature; efficiency; low ionic conductivity</td>
<td>Laboratory testing (kW scale)</td>
</tr>
</tbody>
</table>

* 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 solid polymer electrolyte that allows mobility of positive ions only.

For the hydrogen-oxygen, allows only the positive hydrogen ions, $H^+$, to pass from anode to cathode.

Electrons restricted to flow in external circuit.

Temperature Effect

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

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

<table>
<thead>
<tr>
<th>Form of water product</th>
<th>Temp °C</th>
<th>$\Delta \bar{G}_f$ kl mol$^{-1}$</th>
<th>Max EMF V</th>
<th>Efficiency limit %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid</td>
<td>25</td>
<td>237.2</td>
<td>1.23</td>
<td>83</td>
</tr>
<tr>
<td>Liquid</td>
<td>80</td>
<td>228.2</td>
<td>1.18</td>
<td>80</td>
</tr>
<tr>
<td>Gas</td>
<td>100</td>
<td>225.2</td>
<td>1.17</td>
<td>79</td>
</tr>
<tr>
<td>Gas</td>
<td>200</td>
<td>220.4</td>
<td>1.14</td>
<td>77</td>
</tr>
<tr>
<td>Gas</td>
<td>400</td>
<td>210.3</td>
<td>1.09</td>
<td>74</td>
</tr>
<tr>
<td>Gas</td>
<td>600</td>
<td>199.6</td>
<td>1.04</td>
<td>70</td>
</tr>
<tr>
<td>Gas</td>
<td>800</td>
<td>188.6</td>
<td>0.98</td>
<td>66</td>
</tr>
<tr>
<td>Gas</td>
<td>1000</td>
<td>177.4</td>
<td>0.92</td>
<td>62</td>
</tr>
</tbody>
</table>

Both voltage and efficiency ↓ as cell temperature ↑.
• The thermal efficiency 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 \(T_c = 50\,^\circ\text{C}\).

![Graph showing fuel cell thermal efficiency as a function of operating temperature.](image)

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, actual voltage in the linear (practical) operating range are higher 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,

\[
V_{\infty} - V_{ref} = \Delta V_{oc} = \frac{9RT_{op}}{nF} \ln \left( \frac{p_{op}}{p_{ref}} \right) \quad p_{ref} = \text{atm} \approx 0.1 \text{ MPa} \quad (4.24)
\]

\(T_{op}, \ p_{op} - \text{operating temperature, pressure}\)

**Actual Operating Voltage**

• On the following page, \(V-I_d\) curves are given for H2-O2 fuel cells at two different operating temperatures.
• 70 °C,

![Figure 9.36a: Voltage-current characteristic for typical fuel cell at 70 °C operating temperature (Larminie & Dicks).](image1)

• 800 °C,

![Figure 9.36b: Voltage-current characteristic for typical fuel cell at 800 °C operating temperature (Larminie & Dicks).](image2)

• Some observations:
  - The theoretical maximum or ‘no loss’ voltage is higher at lower operating temperature.
  - The Δ between actual open-circuit voltage and theoretical max is less at higher operating temp.
  - Less fall in actual operating voltage with \( I_o \), in the linear range, at higher operating temp.
  - Net effect: actual operating voltage higher at higher operating temp.
Losses
- The actual operating voltage is degraded by several physical effects:
  - Activation loss: A portion of the voltage is required to drive the chemical reactions at the electrodes.
  - Fuel crossover: Some fuel passes through electrolyte & combines with oxidant - no electricity produced.
  - Resistance loss: 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 solid-oxide fuel cell (SOFC) is a solid-state device with an oxide-ion-conducting ceramic electrolyte.
- Allows high operating temperatures.
- Does not require precious-metal, e.g. platinum, electro-catalysts for the electrodes.

![Diagram of a solid-oxide fuel cell](image)

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

- Electrolyte of zirconia and small percentage of yttria (Y₂O₃)
- Above 800 °C, zirconia is a conductor of oxygen ions (O²⁻)
- 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>
<thead>
<tr>
<th>Fuel cell type</th>
<th>Mobile ion</th>
<th>Operating temperature</th>
<th>Applications and notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline (AFC)</td>
<td>OH⁻</td>
<td>50–200°C</td>
<td>Used in space vehicles, e.g. Apollo, Shuttle.</td>
</tr>
<tr>
<td>Proton exchange membrane (PEMFC)</td>
<td>H⁺</td>
<td>30–100°C</td>
<td>Vehicles and mobile applications, and for lower power CHP systems</td>
</tr>
<tr>
<td>Direct methanol (DMFC)</td>
<td>H⁺</td>
<td>20–90°C</td>
<td>Suitable for portable electronic systems of low power, running for long times</td>
</tr>
<tr>
<td>Phosphoric acid (PAPC)</td>
<td>H⁺</td>
<td>~220°C</td>
<td>Large numbers of 200-kW CHP systems in use.</td>
</tr>
<tr>
<td>Molten carbonate (MCFC)</td>
<td>CO₃²⁻</td>
<td>~650°C</td>
<td>Suitable for medium- to large-scale CHP systems, up to MW capacity</td>
</tr>
<tr>
<td>Solid oxide (SOFC)</td>
<td>O²⁻</td>
<td>500–1000°C</td>
<td>Suitable for all sizes of CHP systems, 2 kW to multi-MW.</td>
</tr>
</tbody>
</table>
Table 9.11: Specific-power range and life for various fuel-cell types (Larminie & Dicks).

<table>
<thead>
<tr>
<th>Fuel cell technology</th>
<th>Specific power (W/kg)</th>
<th>Life, in hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline</td>
<td>100–150</td>
<td>~ 50,000</td>
</tr>
<tr>
<td>Solid polymer</td>
<td>100–150</td>
<td>~ 50,000</td>
</tr>
<tr>
<td>Alkaline (space shuttle)</td>
<td>300–400</td>
<td>3000–5000</td>
</tr>
<tr>
<td>Lightweight cell under development</td>
<td>600–700</td>
<td>TBD</td>
</tr>
</tbody>
</table>

**Regenerative Fuel Cell**

- Based on principle of reverse fuel-cell: hydrogen and oxygen are produced from electrolysis of water.
  - In reality, requires different electrolyte to crack water by electrolysis, so fuel cell cannot be used as such.

- Concept for spacecraft is shown in following diagram,

```
[Diagram showing regenerative fuel cell setup]

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

- System studies show reasonable energy efficiency compared to batteries, and a possible mass advantage 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

<table>
<thead>
<tr>
<th>Energy technology</th>
<th>Round trip energy efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel cadmium battery</td>
<td>70–80</td>
</tr>
<tr>
<td>Nickel hydrogen battery</td>
<td>75–85</td>
</tr>
<tr>
<td>Hydrogen–oxygen RFC:</td>
<td></td>
</tr>
<tr>
<td>Mass optimized design</td>
<td>55–60</td>
</tr>
<tr>
<td>Efficiency optimized design</td>
<td>65–70</td>
</tr>
</tbody>
</table>
5. Radioisotope-Thermoelectric Generators (RTGs)

- The radioisotope thermoelectric generator (RTG) directly converts the high-energy particle-radiation from radioactive decay of an isotope to electrical energy in a semiconductor material:
  - Isotope → Plutonium (Pu) 238,
  - Semiconductor → Silicon-Germanium (Si-Ge)

- Returning to the figure on p. 9-1, the combination of radioisotope-thermoelectric (TE) is most suitable to provide relatively low levels of electrical power, generally < 1 kW, for long durations.

- The technology has been successfully deployed on a number of space missions, primarily for planetary exploration, as listed in the following table,

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

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

\[\text{Data, in part, courtesy of C. D. Cochran, U.S. Air Force, Ref. 12, pp. 4–11.}\]

- Maximum achievable power = 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.

![Cross-sectional diagram of the Cassini RTG](image)

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

![Current-voltage characteristic of RTGs](image)

- The short-circuit current $= 21 \, \text{A}$ at beginning-of-life (BOL).
- Maximum power point $= 4.2 \, \text{V}$
- Maximum power $= 43 \, \text{W}$ at BOL.
- Max power-point shifts to $= 3.8 \, \text{V}$ at end-of-life (EOL).
- Max EOL power $= 38 \, \text{W}$. 

9-34
Isotopes

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

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

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life (years)</th>
<th>Thermal power radiated per gram of isotope (W/g)</th>
<th>Radiation level (Curies/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curium-242</td>
<td>0.49</td>
<td>100</td>
<td>27</td>
</tr>
<tr>
<td>Strontium-90</td>
<td>28</td>
<td>0.25</td>
<td>153</td>
</tr>
<tr>
<td>Plutonium-238</td>
<td>86</td>
<td>0.55</td>
<td>30</td>
</tr>
</tbody>
</table>

- Definition of the Curie: 1 Ci = $3.7 \times 10^{10}$ decays per second
- Note: Plutonium costs ~ $2 \times 10^6$ 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,
  \[ P(t) = P_0 e^{0.693/t_{1/2}} \]  
  where \( P_0 \) = power emitted at beginning-of-life, \( t = 0 \), W
  \( t_{1/2} \) = half-life
  Note: For \( t = t_{1/2} \), \( e^{0.693/t_{1/2}} = e^{0.693} = 2 \) and \( P(t_{1/2}) = \frac{1}{2} P_0 \)

Thermoelectric Generator

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

[Diagram of thermoelectric generator]

- Each leg is of a different type of semiconductor material, one p-type and the other, n-type.

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 electrical potential (open-circuit voltage) results from the Seebeck effect given by,
  \[ V_{oc} = \alpha \Delta T \]  
  and
  \[ \alpha = \alpha_p - \alpha_n \]  
  where \( \alpha_p \) = the Seebeck coefficient for the n,p material combination, V/K.

- The Seebeck coefficient is considered positive 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,

<table>
<thead>
<tr>
<th>Material</th>
<th>( \alpha ), ( \mu V/K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>+375.0</td>
</tr>
<tr>
<td>Si</td>
<td>-455.0</td>
</tr>
<tr>
<td>Fe</td>
<td>+13.6</td>
</tr>
<tr>
<td>Pt</td>
<td>-5.2</td>
</tr>
</tbody>
</table>

9-35
A figure-of-merit, $Z$, of a thermoelectric material is defined as,

$$Z = \frac{\alpha^2}{\rho R k} \left[ \frac{1}{K} \right] \text{ (units: inverse temperature)} \quad (9.5.4)$$

where

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

$\rho$ = resistivity, ohm-m or J-s/m/coul$^2$

$k$ = thermal conductivity, W/K-m

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

$$Z_{np} = \frac{\alpha_{np}^2}{\sqrt{\rho_{np} k_n} + \sqrt{\rho_{np} k_p}} \quad (9.5.5)$$

where

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

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

- For the Si-Ge couple,

$$Z_{np} = 0.001 \quad (9.5.6)$$

- The thermal efficiency is defined as,

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

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

$$\eta_{th} = \left(1 - \frac{T}{T_h}\right) \left[ \frac{\sqrt{1 + Z T} - 1}{\sqrt{1 + Z T + T_c/T_h}} \right] \quad (9.5.7a)$$

where

$$\bar{T} = \sqrt{T_h + T_c} \quad \text{check this} \quad (9.5.7b)$$

- From the electrical-circuit schematic on the previous page, the output or terminal voltage, $V$, is,

$$V = V_{oc} - IR \quad (5.8)$$

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

$$V_{oc} - I_{sc} R = 0$$

or

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

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,

$$V_{mp} = \frac{1}{2} V_{oc} \quad \text{and} \quad I_{mp} = \frac{1}{2} I_{sc}$$

or

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

- The $I-V$, and $P-V$ & $\eta_{th}-V$ curves are illustrated in the following figures,
• Typically, two or more n-p couples are stacked in series, in a single-stage multi-couple assembly as shown in the following diagram, to achieve the operating (bus) voltage to meet load requirements as shown in the second diagram,

![Diagram of Thermoelectric Generator](image1)

**Figure 9.44: Thermoelectric-generator diagram (Patel)**

![Equivalent Circuit and Operating Point](image2)

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

**Temperature Effect & Isotope Depletion**

• Semiconductor material properties are functions of temperature and therefore the I-V curve of a TE convertor shifts with operating temperature, ΔT, as shown in the figure on the following page,

![Normalized Current vs Voltage](image3)

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

• The I-V & P-V curves shift as the isotope depletes 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 measured power output in time from the Voyager II is listed in the following table,

Table 9.15: Power output in time for the Voyager RTG (Patel).

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


**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)

**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 ΔT = 707 K
- Operating temperature: 1273 K hot junction, 566 K cold junction
The following table is a list of $^{238}\text{Pu}$ RTGs for various missions, where the most recent is listed first.

<table>
<thead>
<tr>
<th>Name</th>
<th>Mission(s)</th>
<th>Electrical Power, W</th>
<th>Heat Out, W</th>
<th>Isotope Mass, kg</th>
<th>RTG Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMRTG</td>
<td>Mars Science Lab</td>
<td>~110</td>
<td>~2000</td>
<td>~4</td>
<td>&lt;45</td>
</tr>
<tr>
<td>GPHS-RTG</td>
<td>Cassini (3), New Horizons (1), Galileo (2), Ulysses (1)</td>
<td>300</td>
<td>4400</td>
<td>7.8</td>
<td>55.5</td>
</tr>
<tr>
<td>MHW-RTG</td>
<td>Voyager 1 (3), Voyager 2 (3)</td>
<td>390</td>
<td>7200</td>
<td>~4.5</td>
<td>39</td>
</tr>
<tr>
<td>SNAP-19</td>
<td>Viking 1 (2), Viking 2 (2), Pioneer 10 (4), Pioneer 11 (4)</td>
<td>35</td>
<td>525</td>
<td>~1</td>
<td>?</td>
</tr>
<tr>
<td>SNAP-27</td>
<td>Apollo 12-17 ALSEP (1)</td>
<td>73</td>
<td>1480</td>
<td>3.8</td>
<td>20</td>
</tr>
</tbody>
</table>

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

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

References