

Contents:

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Resources, the Q unit and so on.
 2. Energy Storage
Batteries, mechanical storage, flywheels, etc.
 3. Semiconductors
Introduction to, a little book on the basics.
 4. Thermoelectric Generators
Mainly np bar devices. Generate electricity from heat, also coolers.
 5. Photovoltaic generators.
Photons impinge on np junction devices, etc.
 6. Thermionic generators.
Roughly, vacuum tube diode devices convert heat to electric current.
 7. MHD generators.
Use matter flow (charged plasma) instead of usual wire motion in magnetic field to generate current via Maxwells equations. Might be competitive and more efficient than regular method since fewer moving parts.
 8. Fuel Cells.
 9. Other modes of direct energy conversion.
Nernst effect generator, ferroelectrics, peizos, other ideas.
- Appendix D: basic thermo review as relevant to chapter 4.

Chapter 1: General Introduction.

1. In 1920, coal provided 78% of US energy, oil was 14%, gas was 4%.
In 1973, coal provided 18% of US energy, oil was 46%, gas was 31%.

This shows a rather dramatic shift I would say.

2. The basic Q numbers: One Q = 10^{18} BTU.

Total US energy use in year 1973 was: .08 Q

World use of energy in 1850 was .01 Q/year.

World use of energy in 1977 was .24 Q/year.

Estimates of reserves of say fossil fuels measured in Q are very difficult to make. World petroleum reserves are between 4 and 60Q.

3. Space has been strong motivation for direct conversion because of weight and size requirements.

Chapter 2: Energy Storage.

fact: efficient auto engine is only 15% gasoline to motive power.
fossil fuel plant gets perhaps 40%.

peak-shaving, load-leveling, base load (that which is used 24 hours/day).

1. Long discussion of various types of batteries. I skim only.

2. Thermal storage. England used concrete for electric heat leveling. Water is very good, waxes, salts at higher temperatures. Typical storage is 100 BTU/lb or 10,000 BTU/cubicfoot. This is of course heat of fusion.

3. Mechanical storage: (a) during off-peak, use excess base power to pump water to higher elevation, then bring it back during peak. Overall efficiency is perhaps 70% so use 3 off-peak kWh to make ~~one~~ two on-peak kWh. Obviously high capital costs, basic efficiency is 90%. (b) Use off peak base energy to compress air in mine caverns, then bring it back out again. Efficiency is not mentioned for this. (c) Flywheels, see 1973 Scientific American. You want lightweight strong composite fibers to get very high RPM. Vacuum wheel will go for perhaps 6 months. Auto size systems have been built.

Chapter 3: Introduction to Semiconductors. ,A very long chapter with all the basic solid state stuff. I think I can safely skip this, I know it.

Chapter 4: Thermo-Electric Generators.

History: Seebeck was 1821
Peltier was 1834 , a watchmaker
Lenz was 1838, able to freeze and melt water using Peltier effect
Kelvin was : got relation between effects, predicted Thomson effect.

Appendix D: Principles of Energy Conversion (22 pages)

This is the theory of Osterles, 1964, based on linear approach.

ref 3 deGroot + Mazur: "Non-Equilibrium Thermo" (1962)

ref 4 Prigogine: "Intro to Thermo of Irrev. Processes" (1968)

D.1 Irreversible Thermo.

We are familiar with $J_e \propto \vec{\nabla} V$ and $J_q \propto \vec{\nabla} T$. [Ohm + Fourier law].
In 1931 Onsager proposed generalization to "forces" + "velocities".

$$J_i = \sum_j L_{ij} X_j \quad \text{[the phenomenological relations]}$$

Example is heat flow in non-isotropic material.
force [Callan's "affinity"]

In Callan we found that $\frac{dS}{dt} = \sum f_k j_k$

I see: recall that, in Callan, we had:

$$P_i = \left(\frac{dV}{dx_i} \right) = \text{the true gen force}$$

$$F_i = \left(\frac{\partial S}{\partial X_i} \right) = \text{the "force" in entropy rep}$$

$$F_i = - P_i / T$$

We also had $\vec{f}_k = \vec{\nabla} F_k$ so we could define $\vec{X}_k = \vec{\nabla} F_k$.

$$\text{Then } \dot{S} = \sum \vec{f}_k \cdot \vec{j}_k \Rightarrow \cancel{\sum} T \dot{S} = \sum \underbrace{(T \vec{f}_k)}_{\vec{X}_k} \cdot \vec{j}_k$$

My present guess is

$$\Theta = \dot{S} \quad \vec{X}_k = T \cdot \vec{f}_k$$

Then $D = \Theta T = \text{rate of entropy creation} \times T$.

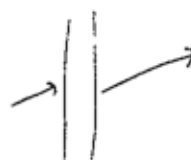
$$\text{units / } dQ = T dS \Rightarrow \frac{dQ}{dt} = T \Theta = \text{power}.$$

So D has units of watts!

Heat thru bar as example:

$q = \text{heat flow} = \text{watts} = \text{joule/sec.}$

$J_s = \frac{q}{T} = \text{total entropy comb.}$

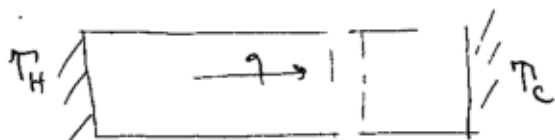


$$J_s(x+dx) - J_s(x) = \frac{q}{T-dT} - \frac{q}{T} = \frac{qT - q(T-dT)}{T^2}$$

$$= q \frac{dT}{T^2}$$

But $\Theta = \frac{dS}{dt} = \frac{dQ}{T dt} = \frac{q}{T dt} =$

Unite stunk! Lets do this right:



$J_q = \text{heat flux} = \text{joules/sec/area.}$

$J_s = \text{entropy flux} = \frac{d^2 S}{dt dA} = \frac{1}{T} J_q$

Ans) $\vec{\nabla} \cdot \vec{J}_s + \frac{ds}{dt} = \frac{ds}{dt} \text{ creation rate.}$

$$\vec{\nabla} \cdot \vec{J}_q + \frac{\partial q}{\partial t} = 0 \quad \Rightarrow \quad \frac{dQ}{dt} = - \int_{cs} \vec{J}_q \cdot d\vec{A}$$

In steady state, Q in section = q out, $\Rightarrow \vec{J}_q = \text{constant along bar.}$

But $\frac{dS}{dt} = \int_{cs} \vec{J}_s \cdot d\vec{A} = \left[\frac{J_s(x+dx) - J_s(x)}{dx} \right] A dx$

$$\frac{dS}{dt} = \frac{dJ_s}{dx} \cdot A dx \quad \Rightarrow \quad \frac{ds}{dt} = \frac{dJ_s}{dx} = \left(\frac{dJ_s}{dT} \right) \frac{dT}{dx}$$

so $\frac{ds}{dt} = + \frac{1}{T^2} \frac{dT}{dx} \cdot J_q$

$$J_q \cdot \frac{d}{dT} \left(\frac{1}{T} \right) = - \frac{J_q}{T^2}$$

So I get $\dot{s} = \frac{1}{T^2} \frac{dT}{dx} \cdot \vec{J}_q = \text{volume rate of entropy creation.}$

More generally, $\frac{ds}{dt} = \frac{1}{T} \frac{dq}{dt} = \frac{1}{T}$

$$\frac{ds}{dt} = \vec{\nabla} \cdot \vec{J}_s = \vec{\nabla} \cdot \left[\frac{1}{T} \vec{J}_q \right] = \vec{\nabla} \left(\frac{1}{T} \right) \cdot \vec{J}_q \quad / \text{since } \vec{J}_q = \text{const.}$$

$$\Rightarrow \frac{ds}{dt} = - \frac{1}{T^2} \vec{\nabla} T \cdot \vec{J}_q \quad \text{a} \quad \frac{\Theta}{\Omega} = - \vec{J}_q \cdot \left[\frac{\vec{\nabla} T}{T^2} \right]$$

OK, OK. At the end of all this he supposes heat + electric.

Review Callan on this. $w_{el} = dW = \vec{F} \cdot d\vec{x} = (q\vec{E})d\vec{x} = -q\vec{\nabla}V \cdot d\vec{x}$

$$\frac{dV}{dx} \quad dV = \frac{|\vec{E}|^2}{8\pi} dx^3 = \frac{\partial \phi}{\partial x} \cdot \phi = \frac{1}{2} \phi \phi = \frac{1}{2} \phi^2 \dots$$

$$\text{so } \left(\frac{\partial V}{\partial \phi} \right) \approx V$$

$$\text{So perhaps } dS = \left(\frac{\partial S}{\partial u} \right) du + \left(\frac{\partial S}{\partial \phi} \right) d\phi = \left(\frac{1}{T} \right) du + \left[-\frac{1}{T} V \right] d\phi.$$

$$\text{Then } \dot{s} = \frac{1}{T} \dot{u} - \frac{\phi}{T} \dot{\phi}$$

$$\vec{f}_p = \vec{\nabla} F_p = \vec{\nabla} \left(\frac{1}{T} \right)$$

$$\vec{f}_i = \vec{\nabla} \left(-\frac{V}{T} \right) \quad \text{so} \quad \dot{s} = \vec{\nabla} \left(\frac{1}{T} \right) \cdot \vec{J}_u + \vec{\nabla} \left(-\frac{V}{T} \right) \cdot \vec{J}_e$$

OK, later I can check any eqn.

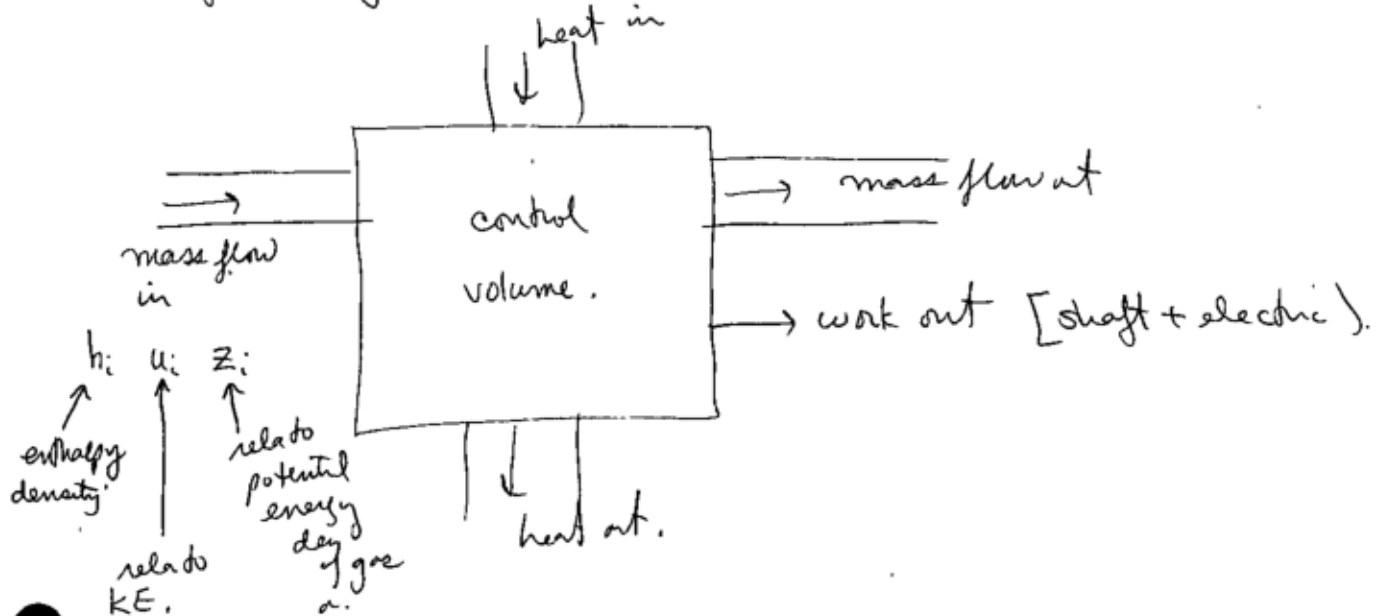
Onsager's $L_{ij} = L_{ji}$ is mentioned

This book is not written at my level ~ too sophisticated.

D.2 Unified Theory of Energy Converters.

P_o = power output of device

Author gets long mess in



Is, a steady state machine.

Claim: $D = T\theta = P_o(\max) - P_o.$

$$P_o = \text{actual power out} = -\underbrace{T_3 X_3}_{\substack{\uparrow \omega \\ \uparrow \tau \\ \text{shaft power in}}} + \underbrace{T_4 X_4}_{\substack{\uparrow I \\ \uparrow \Delta V \\ \text{electric power in}}}$$

$$P_o(\max) = \underbrace{T_1 X_1}_{\substack{\uparrow \text{heat flux from hot reservoir.} \\ \uparrow (1 - \frac{T_c}{T_H}) \\ \text{as usual. (driver)}}} + \underbrace{T_2 X_2}_{\substack{\uparrow \text{mass flux} \\ \uparrow \text{mass of } h, u, z.}}$$

So you can say

$$D = \dot{Q}T = \underbrace{J_1 X_1}_{\substack{\text{heat} \\ \text{flux} \\ \text{input} \\ \text{term.}}} + \underbrace{J_2 X_2}_{\substack{\text{mass} \\ \text{flow} \\ \text{term}}} + \underbrace{J_3 X_3}_{\substack{\text{shaft} \\ \text{work}}} + \underbrace{J_4 X_4}_{\substack{\text{electrical} \\ \text{work.}}}$$

OK, what is going on here? Author is considering an energy converter to be a sort of machine with certain characteristics: in our present example, there are several ways you can "touch" this machine. At the start you cannot say that any of the channels is a priori input or output.

For the picture he shows, there are four things you can do;

- 1) you can supply and drain heat using the two heat reservoirs. This relates to the heat flux term shown above.
- 2) you can affect the mass which flows through the device, perhaps changing its pressure or chemical state somehow (fuel). I think you are not supposed to change its temperature but maybe that is also allowed. Your affecting this mass flow could ~~be~~ be an input or output of energy from this machine.
- 3) Finally, you can put in or take out work and electrical energy.

So all these things could go on at once. The above equation then tells you how to compute the rate at which entropy is dissipated by this machine.

However, we are usually only interested in the simple case in which only two of the above flux/force terms are present. Call one the input, the other the output, and write:

✓ sym d.

$$D = J_i X_i - J_o X_o \quad \text{and efficiency} = J_o X_o / J_i X_i$$

Onsager:

$$J_i = L_{ii} X_i + L_{io} (-X_o)$$

$$J_o = (L_{oi}) X_i + L_{oo} (-X_o).$$

└ cannot be zero for machine to "convert".

So
$$\begin{pmatrix} J_i \\ J_o \end{pmatrix} = \begin{pmatrix} L_{ii} & -L_{io} \\ L_{oi} & -L_{oo} \end{pmatrix} \begin{pmatrix} X_i \\ X_o \end{pmatrix}$$

Here, both faces are the independent's.

Can also write as

$$\begin{pmatrix} X_o \\ J_i \end{pmatrix} = \begin{pmatrix} \alpha_1 & -R_1 \\ C_1 & \alpha_1 \end{pmatrix} \begin{pmatrix} X_i \\ J_o \end{pmatrix}$$

($\alpha_i = \alpha_1$ by Onsager)

Here, output face caused by input face ["even class"].

Also

$$\begin{pmatrix} X_o \\ X_i \end{pmatrix} = \begin{pmatrix} \alpha_2 & -R_2 \\ C_2 & \alpha_2 \end{pmatrix} \begin{pmatrix} J_i \\ J_o \end{pmatrix}$$

$$D = C_1 X_i^2 + R_1 J_o^2$$

Here output face caused by input flux ["odd class"].

α = an interaction coeff.

$$D = C_2 J_i^2 + R_2 J_o^2$$

R = a resistance

C = a conductance.

Ideally you would like to have $R=C=0$ so no dissipation!

uncoupled: you can twiddle R, C separately, hence maybe you could get $D=0$.

coupled: R, C are coupled, cannot make $D=0$.

Example: picture shows a dam where water is run through a turbine to generate mechanical power. The two terms here are mass flow with associated potential energy difference (assume very slow flow rate so no kinetic), and the shaft with angular velocity and torque. In this system, C = leakage conductance of water through turbine. I.e., having $C \neq 0$ hurts because uses up mass flow by generates no work. R = the shaft friction effect. The parameter α is mass displaced per revolution of turbine and is the interaction parameter.

Point made: example of R, C uncoupled and even class (X 's are dy and torque)

What you want is to minimize the dissipation D which is a measure of your loss! I.e., it measures $P_o(\text{max}) - P_o(\text{actual})$. How close can you get to the theoretical maximal power!

In the water driven turbine example, since R and C were uncoupled, you could at least in principle get them both very small and thus approach the theoretical max efficiency (which I guess is 100% for such a machine).

Example 2: Thermoelectric generator. A temp gradient (driving force) produces a potential gradient (output force), so this is even class machine. The design shown however is coupled: you want to minimize R (electrical resistance) by making area large on the legs, but you want to minimize C (Fourier heat conduction loss) by making same area small. You cannot win on both, so this is a coupled device.

Example 3: A DC electric generator. Here the input flux is current I , the output force is .. STOP.

The output force is voltage out, the input flux is angular rotation of shaft. This is odd class. R = internal resistance, C = shaft friction inverse. Again, uncoupled so can approach ideal efficiency, i.e., can make dissipation vanish.

Example 4: Nernst generator. This thing generates a voltage output due to crossed thermal and magnetic fields! A Thermomagnetic device. Output is voltage (force), input is heat flux q , so odd class. Like the thermoelectric devices, R and C are electrical resistance and heat conductance and are coupled, so you cannot get ideal efficiency from a Nernst.

About efficiency: There is of course a theoretical efficiency that we cannot do anything about (eg, the Carnot efficiency). But the second question is: what is your ~~effectiveness~~ effectiveness towards achieving this theoretical max efficiency.

I.e., even when $D=0$ you are not getting 100% efficiency because, eg, your low temp reservoir would have to be at absolute zero. $D \neq 0$ is a measure of how far away you are to the theoretical max.

So

$$\eta = \frac{J_o X_o}{J_i X_i} = \text{effectiveness}, \quad = 1 \text{ when } D=0.$$

Given your set of three constants for any system (like the samples above) you can compute the effectiveness. You can find the output flux which maximizes this effectiveness, and thus get max effectiveness formulas. The result for either even or odd class machines is this:

$$\eta_{\text{max}} = \frac{\sqrt{1+\beta_1} - 1}{\sqrt{1+\beta_1} + 1} \quad \text{where} \quad \beta_1 = \frac{\alpha_1^2}{R_1 C_1} \quad \leftarrow \text{figure of merit.}$$

$$\text{as } R_1 C_1 \rightarrow 0, \quad \beta \rightarrow \infty, \quad \eta \rightarrow 1. \quad =$$

Angrist Chapter 4: Thermoelectric Generators.

4.1 History . Seebeck voltage, Peltier heat, Thomson heat, etc, very brief.

4.2 The Thermo-electric Effects.

A material has a certain property called $\alpha(T)$, the thermoelectric power. If you make a junction of two materials, the difference in these alphas at some T is called the Peltier coefficient. If you integrate this alpha difference from hot to cold (or around a loop), you get the Seebeck voltage. This is how a furnace thermocouple generates its few millivolts to activate a switch.

If you run a current through a junction between two materials at T (or if the junction generates the current somehow, does not matter), you find that the junction gives off or absorbs heat, the Peltier heat.

The Peltier coefficient Π is just T times the Alpha, so $\Pi_{ab} = T(\alpha_a - \alpha_b)$, and the Peltier heat given off at a junction is just this Π times the electric current. Thus, Peltier is interaction between an electric current and a material gradient at constant system temperature. Seebeck on the other hand requires a temperature difference and a material difference, no current involved.

The Thomson effect involves heat transfer where there is a current and a temp gradient, but no material gradient. Again, the effect is proportional to current and temp gradient. The coefficient is related to the temperature derivative of the alpha coefficient.

<u>Seebeck:</u>	material and temperature gradient	(no potential gradient, no I)
<u>Peltier:</u>	material and potential gradient	(no temp gradient)
<u>Thomson?</u>	potential and temperature gradient	(no material gradient)

Thus you see that each of these "effects" involve two of the possible three gradients. A general effect would involve all three. Of course all are really facets of the same thermo process, so you expect coefficients to be related in a very simple way, which is in fact the case.

4.3 Solid State Description of Thermo effects.

$$V_{AB} = \int_{T_1}^{T_2} (\epsilon_A - \epsilon_B) dT = \text{seebeck voltage.}$$

$$\Pi_{AB} = T(\epsilon_A - \epsilon_B) = \text{Peltier}$$

$$\Sigma_A = -T \frac{d\epsilon_A}{dT} = \text{Thomson}$$

$$J_q = I \cdot \Pi_{AB}.$$

$$J_q \sim \Sigma_A A T \cdot I.$$

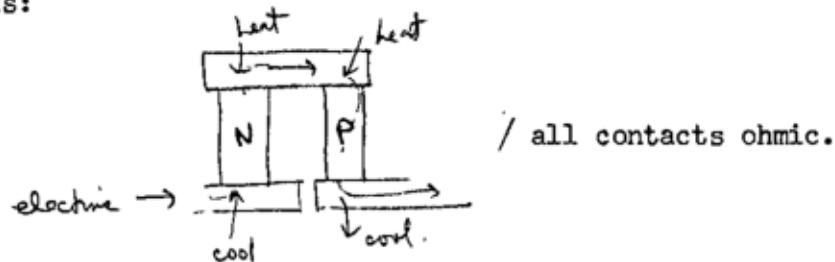
$$\text{So } \begin{cases} \epsilon_A = \text{Seebeck} & [\text{also called } \alpha_A] \\ \Pi_A = T \epsilon_A = \text{Peltier} & (\sim 1 \text{ volt}) \\ \Sigma_A = -T \frac{d\epsilon_A}{dT} & (\text{volts}/^\circ\text{K}) \end{cases} = \left(\frac{k}{e} \right) \left[\frac{(\epsilon_F - \epsilon_V)}{kT} + 2 \right] = \frac{1}{e} [(\epsilon_F - \epsilon_V) + 2kT]$$

$86 \mu\text{V}/^\circ\text{K} \nearrow \approx 2$

In this section we see the actual mechanism which causes these thermo effects. Basic object of interest is a metal-semiconductor junction. Suppose electron goes from metal into n-type semi. Assume contact is ohmic so ignore little flare in band diagram. The metal of course has a fermi level, which continues into the semi. But electrons cannot exist at the fermi level in the semi because it is in the middle of the gap. Electrons have to be sent up to the conduction band in order for them to get into the n-type bar. The junction itself must supply thermal energy to get these entering electrons up to the conduction band. Thus you get Peltier cooling at a junction where electrons go from metal to n-type. The Peltier coefficient is roughly dE/e where dE is the energy jump electrons must make. Actually, other factors obviously come into play, but this is simplest idea.

Similarly, where holes enter a p-type bar, you get cooling because those holes take a jump down to flow in the valence band. Where electrons enter a p-type bar, you get Peltier heating.

So consider an NP type device. Where electrons enter the n-type you get cooling. Where electrons leave the n-type you get heating. Where ~~holes~~ electrons enter the p-type you also get heating, etc.,. Thus basic design of a heater/cooler looks like this:



Thus you can chain these things together. Notice that there are no actual NP junctions.

The Seebeck and other coefficients have opposite sign for N and P type bars, mainly due to sign of majority carrier. This is a way to tell what type material you have.

Even intrinsic has a Seebeck because holes and electrons have different mobilities. General result for Seebeck is given for any semi.

4.4 Analysis of a Thermoelectric Generator.

Here an obvious NP generator is analyzed. We find the $T(x)$ temperature distribution in the presence of drawn current I . There is Joule heating in the N and P bars due to ~~thermal conductivity~~ resistivity ρ . There is also heat flow through the bars due to thermal conductivity λ . Simple model assumes perfect contacts, so all loss is in the bars themselves. The Seebeck coefficient α is just $\alpha_n + \alpha_p$ both positive numbers, ie, things are in series so so speak. Peltier is T times this sum, so it actually works.

Efficiency: Now comes the crucial question. Define $\eta_t = P_o/q_H$. Ie, for one watt of heat energy input at the high temperature, how many watts might you get out in electrical power?

Note: Quick review of heat engine efficiency. Defined by $\eta = \text{workout}/\text{heat in at } T_H$. No engine can be more efficient than the Carnot engine so $\eta = dT/T_H$. That is, $\eta = 1 - T_C/T_H$ (see Z page 235). This is only achieved only if engine operates perfectly reversibly and there is zero entropy dissipation. If entropy is generated, (ie, if there is some irreversibility in your heat engine), then your actual efficiency will be less than this theoretical Carnot max.

So if your thermal engine acts between 600°K and 300°K , the theoretical max on efficiency is 50%. BUT, the real question is: how close can a particular

device come to the theoretical max?!!

For device considered here, $\eta = \frac{P_o}{q_H}$ (Theo. max = $1 - \frac{T_c}{T_H}$).

Let $R =$ bar total resistance (funs of g 's)

$K =$ bar total thermal conductance (funs of λ 's).

$\alpha = |\alpha_n| + |\alpha_p| =$ effective Seebeck.

Then, $R_o =$ load resistance.

$$m' \equiv R_o/R.$$

Let $Z \equiv \frac{\alpha^2}{RK} =$ figure of merit.

If you choose geometry to minimize RK , hence max Z , you get

$$Z_{\max} \equiv Z^* = \frac{(\alpha_n + \alpha_p)^2}{(\sqrt{S_n \lambda_n} + \sqrt{S_p \lambda_p})^2}.$$

↑ set by materials.

Then:

$$\eta = \dots$$

If you next optimize R_o (ie, m'), you get

$$\left(\frac{R_o}{R}\right)_{\text{opt}} = m'_{\text{opt}} = (1 + Z^* T_{av})^{\frac{1}{2}}.$$

$$\eta(\text{opt}) = \frac{(m'_{\text{opt}} - 1) \frac{\Delta T}{T_H}}{m'_{\text{opt}} + T_c/T_H} \rightarrow \frac{\Delta T}{T_H} \quad \text{as } m'_{\text{opt}} \rightarrow \infty$$

$Z^* \rightarrow \infty$
 $RK \rightarrow 0.$

Still I have no idea what this is as a practical number. Book goes on to consider multi-stage efficiency calculations etc. I skip that and go to page 156 for some numbers!

Design Example (thermoelectric electric power generator).

$$T_H = 327^\circ\text{C} = 600^\circ\text{K}$$

$$T_C = 27^\circ\text{C} = 300^\circ\text{K}$$

$$\eta(\text{theo}) = 50\%$$

n, p materials are Bismuth Telluride + Antimony

$$|\alpha_n| + |\alpha_p| = 195 + 230 = 425 \mu\text{V}/^\circ\text{C}$$

$$Z^* = 2.26 \times 10^{-3} / ^\circ\text{C}$$

optimize geometry.

$$K \approx 30 \text{ mW}/^\circ\text{C}$$

$$R \approx 3 \text{ m}\Omega$$

$$m'_{\text{opt}} = 1.42 \text{ for max } \eta.$$

$$V_{\text{out}} = \alpha \Delta T \text{ (Paul Seebeck)} = 128 \text{ mV}.$$

$$I_{\text{opt}} = 19.2 \text{ amps.}$$

$$P_{\text{out}} = 1.44 \text{ watts}$$

$$q_H = 13 \text{ watts}$$

$$\eta = 11\%$$

Book goes on to consider power out optimization and then power density optimization. (power/cm²). You see that a typical 1 cm scale device can deliver 20 amps at 1/10 volt with about 10% efficiency at 600-300 temp difference, certainly quite respectable I would say. Materials seem relatively cheap? Maybe not.

Idea: let your two reservoirs be the earth at depth 1 foot and depth 10 feet. In winter and summer you run your heat engine in reverse directions, always generate electricity! Obviously you need some economics on this.

4.5 Analysis and Design of Thermoelectric Cooler.

Similar to last section for thermo generator. The coefficient of performance will be $\beta = q_c/P$, the heat removed at low temp divided by motor or input power. As before, you optimize geometry. Then you optimize on input current I . Questions of interest are:

- 1) what is max rate that heat can be pumped out?
- 2) what is max ΔT that can be maintained, say versus ambient.

Design Example [Thermoelectric cooler].

● $T_H = 327^\circ K$, ambient $= 300^\circ K = 27^\circ C$.

└ to get connection into ambient

$$T_C = 273^\circ K = 0^\circ C$$

Want 3 watts of cooling, $q_c = 3 \text{ watts}$.

Use same nice P-N materials.

$$I^* \approx 29 \text{ amper}$$

$$\beta^* = \left(\frac{q_c}{P_{in}} \right) = .32$$

Each cell needs $P_{in} = 2.35 \text{ watts}$ to make .15 watts of cooling.

● So 4 cells. Not sure what β_{max} is here, but I know

β can be > 1 .

4.6 The Figure of Merit.

Why are semiconductors best? Consider the continuum from insulator to metal conductor. It turns out that the seebeck coefficient decreases as you increase n , but the resistivity also decreases and that is good. Generall it seems that merit figure Z maxes out in the region of n that is semiconductor.

Generall the doping is roughly $n = 10^{18}$ to 10^{21} which is high compared to say epitaxy of 10^{15} . Typical Seebeck is 250 mV/degree.

Rollie Ure and Heikes did a ~~xxxxxxx~~ paper on this subject, no its a 1961 book: Thermoelectricity. They figure that a factor of 10 improvement in the figure of merit for these semiconductor materials would make thermal electric and cooling competitive with conventional methods in both areas! Recall that this Angrist book is 1976. I wonder what improvements have been made so far???

4.7 Actual Devices.

Here the Air-Vac design is considered, along with various peripheral probelsm such as thermal expansion. A Little Coleman jobbie that looks like a lantern can generate 9 volts at 200 mW for 24 hours. Teledyne company makes radio-isotope driven thermal gnerators for Viking and similar machines. Typical parameters are: $800^\circ K = T_H$, $180^\circ K = T_C$, input power 4000 watts (thermal), electric output power 400 watts. Density of 10 watts/kg weight. Materials are selenides.

A little cooling system is also discussed, . End of chapter.

Journals appearing in the references;

Journal of Applied Physics

Journal of Heat Transfer

British Journal of Applied Physics

Intersociety Energy Conversion Engineering Conference

Transactions of the American Society of H,R and AC Engineers

Chapter 5: Photovoltaic Generators

This is the first material I have read on this important and crucial form of solar energy. The basic ideas are quite simple:

You know that in a np junction there is a space charge region of strong electric field. If a photon "hits" in this physical region, it can create an electron-hole pair which is then separated by the field and is driven out, so to speak, where it appears as a current.

The current caused by incident photons is called I_s , or density J_s . Essentially except for certain loss factors this current density is $J_s = e J_{ph}$ where J_{ph} is the flux of photons with energy greater than the gap. Typically this is $2/3$ of all the photons from the sun.

What are the loss factors (see 5-30). The factor $(1-r)$ is reflection loss at the surface, which you usually get rid of with a matching layer. Then the factor $(1 - \exp(-\alpha L))$ represents the fact that not all photons are absorbed where you want them to be absorbed, ie in that junction. There are other semiconductor inside losses which are grouped into another factor.

Generally speaking, however, the photo-current is reasonably close in value to e times the useable photon flux.

Now this photo current simply adds to the normal junction current which is nonzero if some voltage is on the junction, ie:

$$J = J_s - J_0 \left[e^{eV/kT} - 1 \right] \Rightarrow V_{oc} = \frac{kT}{q} \ln \left(\frac{J_s}{J_0} + 1 \right)$$

Here J_0 is the usual saturation current (density). If your photojunction is open circuited (oc), then the above tells you the open circuit voltage your diode will generate! If no light, you get no voltage out. It really is simple.

The next step is to write $P = JV$ (power density), and to find the voltage and current that cause max power. Then you can use this to get the max efficiency. Roughly speaking you get this:

$$\text{efficiency} = \frac{V_{mp} J_s}{N_{ph} E_{av}}$$

where V max power and E average of each incoming photon. Finally you can roughly set $J_s = n_{ph}$ the number of useable photons. This suggests a theoretical limit on such devices: since $E_{av} = 1.2$ eV and since $V_{mp} = .4$ volts you are already down to 33%. Then the useable photon fraction is about $2/3$ so you are down to about 22%. Devices have been made easily with 10% and up to 15%. The main problem of course is the costg of such devices!

Device Design: you of course want a large area of junction close to light source. Use a p substrate with a thin n layer on the surface, only .1 micron thick. This distance seems to optimize the number of photons absorbed in the useful volume. Perhaps you could bias the thing with the battery charged to get the volume idealized.

The substrate contact is easy, the surface contact is usually a grid of metal layed on the surface and of optimal width and pattern.

A practical design is mentioned. A crucial number is this: the useable photon flux when multiplied by e is 48 mA/cm^2 for silicon. Perhaps this is a reasonable value and not optical. So 50 mA/cm^2 is what you are going to get out of 1 cm^2 , less inefficiency (which in example reduces this to about 13 mA/cm^2)

The max power output voltage is about .55 volts, and the max power current is about 12 mA. Thus we are getting about 7 mW/cm^2 . What do I think of that!? This becomes 70 watts/m^2 which is in fact about 7% of the 1000 watts/m^2 .

Typical efficiency = 10%

Typical electric DC power generated = 100 watts/m^2 of silicon. Silicon of required grade costs \$100/lb.

Fabrication of such cells is discussed, the CdS cell also mentioned as being cheaper.

Present idealized cost of cells is about \$1500 per $\text{m}^2 = 100 \text{ watts}$. Think of this as \$15,000 for a kilowatt. Obviously no one can really afford this for their roof. Installed nuclear plant is only \$1500/kw they say, so that is the problem.

Mass production methods however might make a silicon farm feasible. This is something to look into, articles are referenced:

Cherry, J of Engineering for Power 94 A 2 April 1972.

Other details

- 1) even if 15% efficiency is reached, you still have problem of weather degradation of the cells and you have to always be replacing them.
- 2) a mass market is needed before mass production will begin on these things. At present the \$15000/kw installation figure is just too high compared to the \$1500/kw for even nuclear.
- 3) Perhaps some other material will have a better band gap and be able to use more of the solar photons.
- 4) water and clouds affect solar flux. Even with an ideal gap at 1.70 eV, the max theoretical efficiency of a cell seems to be about 32%. This is pretty good though, in my opinion. The real factor is cost, not efficiency as long as in reasonable range.

This chapter was a good introduction to the subject. About 50 pages. Many references given, but book is a little out of date, being 1976.