Don Lancaster's Hardware Hacker

May, 1993

It has to build upon all the underlying foundations of math, physics, chemistry, and the other engineering disciplines.

This month, I figured I'd take a back-to-the-basics tack over a topic that has been causing more than its share of helpline grief lately.

In short, we are long past overdue in taking a close look at the...

Fundamentals of Thermodynamics

As our figure one shows us, a *heat* engine is some device or scheme that accepts thermal energy at a high input source temperature T_H , outputs some useful mechanical work, and finally rejects remaining thermal energy to a lower output sink temperature T_L .

Nearly all auto and airplane power sources use heat engines, as do most electrical generators. Variations on the heat engine theme lead us to heat pumps, icemakers, vacuum systems, refrigerators, and compressors.

And, for that matter, to life itself.

The study of heat engines is known as *thermodynamics*. While more of a mechanical engineering topic than an electrical one, (A) EE students have to take at least one thermo course; (B) nearly all modern heat engines need lots of support electronics; (C) many home power and new energy recovery schemes are actually heat engines in disguise; and (D) knowing the thermo fundamentals lets you instantly sort out the perpetual motion ripoffs and the outrageous pipe dreams from the realities of practical physics and real world economics.

We should note up front that more people have spent more time hacking heat engine ideas than on *any* other engineering topic. The field has been studied to death, and there are *tons* of readily available literature out there waiting for your immediate access.

Unless you can bring something genuinely, truly, and astonishingly new to the table, the chances are your "new" heat engine concept has gotten thoroughly trashed over decades ago. Or even centuries before.

Ferinstance, I got this model heat engine in the mail. It was a clever demo of how crucially important the *reversibility* problem is in preventing you from getting useful economics. Reversibility is a very sticky thermo problem which was first solved in a brilliant breakthrough analysis first done by James Watt. In 1784.

Thermo Laws

Any study of thermo starts off with the laws of thermodynamics. While unproven, nobody has *ever* been able to find *any* exception to these laws. At least not on an everyday scale.

Countless individuals have blown incredible amounts of their time and money trying to crack these thermo laws. All of them have failed totally.

Without exception.

The laws are pretty fundamental, and range well beyond heat engines. For instance, cell biology, the very life process itself, photosynthesis, the chemical reactions, and much of solar power all must obey these laws.

Glibly parapharased, the laws are (A) You cannot win; (B) You cannot break even: and (C) Sure, the dice are crooked, but this is the only game in town.

Uh, more formally: Left to its own devices, heat energy always travels from higher temperatures to lower

Steam calliope sources Micropower oscillators Avoiding energy scams Thermodynamic basics The comm trade journals

ones. Systems always tend to their most chaotic and lowest energy level states. Energy can neither be created nor destroyed in any thermodynamic process.

If you do build a heat engine, only a small fraction of the total energy can ever be recovered as useful work; all the rest is irretrievably lost as low grade heat.

Ah yes, that fraction. How big and just how much? Enter one of the most brilliant hardware hackers of all time by the name of Sadi Carnot. As most hardware hackers, Carnot did not have the foggiest idea what he was really doing. It took "them" decades to finally understand how utterly profound and fundamental Carnot's discovery was.

Typical heat engines use a *working fluid*. More important heat engine fluids include air, steam, ammonia, freon, mercury, nitrogen, hydrogen, helium, or even liquid sodium. The working fluid goes through a number of individual steps or *processes* to trace out a *cycle*. Obviously, a heat engine cycle must close upon itself and return to initial conditions such that useful work can continue.

These thermodynamic cycles can usually be graphed in your choice of a *pressure-volume* (*p-v*) diagram or a *temperature-entropy* (*t-s*) diagram.

The area inside the cycle on either

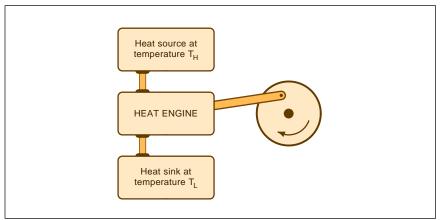


Fig. 1 – A HEAT ENGINE accepts energy from a high temperature source, does useful mechanical work, and then will reject a portion of that energy to a lower temperature sink. Only a fraction of the energy can be converted.

64.1

Hardware Hacker

As one process in a heat engine cycle, assume you have a fluid you wish to compress by adding weight to the piston such that your piston drops by exactly one foot ... On your first try, you throw an eight pound brick on the piston and note that the piston does in fact drop by one foot. You have done 8.0 foot pounds of work. As we will shortly see, this is a useless and **BADLY IRREVERSIBLE** process, because one-half of your work will get lost as irrecoverable low grade heat... On your second try, you place a one pound rock on the piston, wait till things settle, and then add another one pound rock. You will still need eight pounds of rocks, but this time, the work needed is only 8/8 + 7/8 + 6/8 + 5/8 + 4/8 + 3/8 + 2/8 + 1/8 = 4.5 foot pounds of work. This is a useful but **MODERATELY IRREVERSIBLE** process in which one-eighth of your work gets thrown away... On your third try, you place a feather on the piston, wait till things settle, and add another feather. You still need eight pounds of feathers, but this time the work needed is only the tiniest amount above 4 foot pounds. This is a FULLY **REVERSIBLE** process in which virtually none of your work gets thrown away ... Any fully reversible scheme to compress or expand a fluid is also called an ADIABATIC process. Heat is neither added nor removed

in any reversible adiabatic process.

Fig. 2 – EFFICIENT HEAT ENGINES demand that all the processes used be fully reversible. Here are some good and bad examples.

a p-v or t-s diagram is related to how much useful work you can extract from your heat engine. The *efficiency* of any engine is the ratio of the useful work you extract compared against the energy which you must dump as low grade heat.

Numerous heat engine cycles have been dreamt up. The *Otto* cycle gets used in gasoline engines, while the *Diesel* cycle obviously gets used in diesel power plants. Electric power turbines use a *Rankin* cycle. Or some multi-stage improvement thereon. A lot of alternate energy people get real excited over a *Stirling* cycle, since it is an "external combustion" type of engine which can accept heat from diverse or low grade sources.

Every few years or so, somebody reinvents the old Stirling engine, and then builds a bunch of prototypes that just barely miss. Then they will just barely go bankrupt. To date, the old Stirling cycle has largely proven to be both a sucker bet and an economic rathole. Except possibly for arcane cryogenic cooling aps.

What Carnot did was ask "What is the finest theoretical thermodynamic cycle you could possibly create?" and "What are the efficiency limits to the finest possible cycle?"

It was obvious that each part of a Carnot cycle had to be lossless. More precisely, all the processes involved had to be *reversible*. You have to be able to undo anything you just did without losing any heat to friction or other losses. This means "no sudden moves" and "no rapid changes", with everything altering as incrementally and as slowly as possible. It will also mean zero friction, lossless seals, and perfect insulation.

Figure two shows you more on the concept of reversibility.

Ferinstance, say you want to use a piston to compress the gas inside a non-insulated cylinder. Some work is needed to get your gas reduced to a required size. Any work above that is lost as low grade heat.

Say you build up your cylinder and throw an eight pound weight on it.

You note that this particular piston happens to drop by a foot, doing work to compress your gas. In this case, eight foot pounds of work were used, since the eight pound weight dropped by one foot.

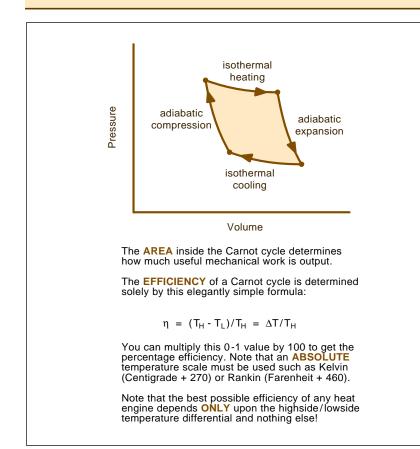
Is this the best you can do? Say instead, you put a one pound weight on, waited till things settled down, added another one pound weight, and so on. You now have the first pound going a full foot and the final pound only going an eighth of a foot. Your total work is 8/8 + 7/8 + 6/8 + 5/8 + 4/8+ 3/8 + 2/8 + 1/8 = 4.5 foot pounds of total work input.

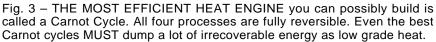
Yet, in each case, you compressed the gas by the same amount, raising its energy state by the same value. The extra 3.5 foot pounds of work has dropped through that irrecoverable low grade heat rathole.

In both examples, you do have an irreversible process. But your second one is clearly much better. As a third try, put a feather on the piston. Wait till things settle, and then put another feather on the piston. Repeat this for eight pounds of feathers, and you will also end up with the gas compressed by a foot. And only 4.0 foot pounds of total work will be needed. This is a reversible process and the best you can do. And twice as efficient as your first attempt.

One more time: Ya gotta be able to undo what you just did. At all times, you do have to be willing and able to

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stuff the Genie *back* into the bottle. That's what reversibility is all about.

There are several rather important reversible processes. One of these is called an *isothermal* process, where everything takes place at a constant temperature. The heat energy receiver has to be at a temperature only a tad lower than the energy source. And the heat source has to be so large that taking a small amount of energy out of it does not significantly change its temperature.

A second is an *adiabatic* process, in which heat energy is neither added nor removed. *For a full reversibility, any compression or expansion of a working fluid should be adiabatic.*

At any rate, the Carnot cycle uses fully reversible processes to trace out the best possible of theoretically ideal heat engine cycles.

Figure three shows you some more Carnot cycle details. Once again, this one is the best possible one you can ever build. Why? Because of the full reversibility. You just can't get better than this. If you think otherwise, you are flat out wrong. Guaranteed.

In the Carnot cycle, you start with a working fluid at a low temperature. Then you adiabatically compress that gas by doing work on it. Typically, the new external energy required can come from a flywheel or a second cylinder in the engine. Compressing the fluid raises its temperature and reduces its volume. *Extreme care is needed to neither add nor remove any heat energy during compression*. The temperature rise has to result solely from the volume reduction itself.

Compression will continue until a temperature very slightly under that of the heat source is reached.

After compression, an isothermal process transfers hot heat energy into the fluid, expanding it and increasing the pressure. The temperature, of course, stays the same. In the third step, your gas adiabatically expands while delivering useful output work.

The fluid volume goes up and the temperature goes down.

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and closing the cycle.

Once again, that area inside the curve on the p-v diagram determines how much work gets delivered.

Since every process is reversible, you can input high temperature heat energy to produce output mechanical work. Or, you can input mechanical work to pump heat from the low side to the high side.

swapping the high side and low side destinations.

When you go through the math (the derivation takes a full lecture hour in any university physics course), this stunningly elegant and simple result pops out...

$$\eta = (T_{\rm H} - T_{\rm L})/T_{\rm H}$$

Restated in English: The very best

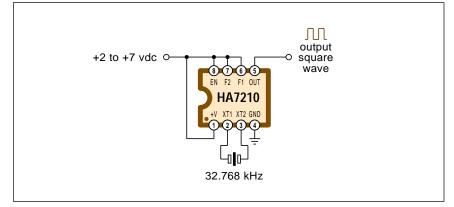


Fig. 4 - MICROPOWER CRYSTAL OSCILLATOR by Harris Semiconductor only needs five microamps of supply current from a source as low as two volts. It costs under a dollar. Free sample kits are available.

iency you could ever get at engine is determined e ratio of your source to the sink temperature.

what the cycle, fluid, or ng used!

ey point: To get useful any heat engine, you'll lots more energy away ble low grade heat.

mple, a modern auto theoretical efficiency of with something like 38 g a typical real world is at the flywheel. The ency as a transportation lower.

One minor gotcha. You bsolute temperatures for rmula to work. Absolute in are 460 degrees above bsolute degrees Kelvin es above Centigrade.

ercentage efficiency is a s the efficiency stated as m 0.0 to 1.0.

at the formula ourselves. street is an impressive vell that's spewing forth 25 degrees F. Could we ctricity out of it?

e local average ground is 75 degrees (The well sits in the Upper Sonoran life zone.) Your best possible energy recovery efficiency here would be ...

((125 + 460) - (75 + 460))/(125 + 460) = .085

Or a mere 8.5 percent, under ideal conditions. That's assuming a perfect Carnot cycle. In the real world, you'd be lucky to get a tiny fraction of that. Say three percent net. Thus, for every kilowatt hour you generate, you have to throw thirty-two of them away!

Sadly, it does make perfectly good sense to ignore some \$20,000 worth of electricity a year just by dumping it into the Gila River. Why? Because any real-world recovery project of this size and temperature differential could *never* pay for the engineering, materials, operating costs, flood zone risks, and the time value of money needed to properly do the job.

Is there any way you can beat the thermo laws? Generating electricity won't hack it, since you can always use your electricity to run a motor, which instantly gets you back to a

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heat engine.

You can switch to a *binary* or even a *trinary* cycle which uses multiple stages and different fluids. But these often will only marginally improve the efficiency while doubling costs.

The only other way I know of is to do something useful with the rejected low grade heat. Say by heating water, equalizing process temperatures, or starting your own catfish farm.

A solar panel that also heats water should have much better economics than one that solely generates some electricity. Schemes such as these are sometimes called *cogeneration* and they are now a very hot topic indeed. There is even a *World Cogeneration* trade journal.

A Reality Check

So, how do you separate the "real" heat engines from the scams and the wishful thinking daydreams? First, calculate your Carnot efficiency and see what this reveals about the claims involved. Be especially suspect of "this is not a heat engine," or "the thermodynamic laws do not apply to me" evasions.

Then carefully look at the *p*-*v* or *t*-*s* diagrams (these will *always* be very obvious on any legit device). Then check carefully for anything which is obviously non-reversible.

Any sudden changes or purposely adding coolant to close a cycle are dead giveaways that all is not well.

Always ask "Can each and every process step in use be run backwards just as well as forwards?"

Then you throw in some economic analysis. Most crucially your time to breakeven. This is the length of time which is needed for your generated power to pay for the materials, the design, and time value of the money needed to create the device. Assume that 17.58 watts is a heating rate of one BTU per minute, and raises one pound of water by one degree F. And that a nickel per kilowatt-hour is a workable ballpark avoided cost for electricity. And that a gallon of water weighs eight pounds. And that the time value of money normally triples the cost of a project.

Note that the time to breakeven can easily be infinite! If you produce less electrical revenue per year than the interest on the construction financing

NAMES AND NUMBERS

Dialog 3460 Hillview Avenue Palo Alto, CA 94304 (415) 858-2700

Electric Power Research Inst. PO Box 10412 Palo Alto, CA 94303 (415) 855-2000

GEnie 401 N Washington Street Rockville, MD 20850 (800) 638-9636

Grass Valley Group PO Box 1114 Grass Valley, CA 95945 (916) 478-3000

Harris Semiconductor 1301 Woody Burke Rd CB 1-25 Melbourne, FL 32902 (407) 724-3739

Hitachi 2000 Sierra Point Parkway Brisbane, CA 94005 (415) 589-8300

Industrial Laser Review One Technology Park Drive Westford, MA 01886 (508) 692-0700

Navtech Books & Software 2775 S Quincy Street, Ste 610 Arlington, VA 22206 (800) NAV-0885

Power Engineering 1250 S Grove Avenue, Ste 302 Barrington, IL 60010 (708) 382-2450

is costing you, the longer you run, the more you will lose.

Finally, be extremely wary of the word "Stirling". When and where it happens to occur.

My favorite popular thermo book is *Heat Engines* by Sanford and found in the Doubleday Science Series.

Beyond this one, pick up any of the dozens of college level course texts. Important thermo resources include the SAE Library from the Society of Automotive Engineers, and the EPRI Publications from the Electric Power Research Institute.

Of the many trade journals, *Power Engineering* is typical; it targets large scale electrical generation.

Communications Resources

Where can you go to get a crystal for a pager? Or to find out more on fiber optic comm? Or information on wireless modems? Or phone testing? **Ragtime** 4218 Jessup Ceres, CA 95307 (209) 668-0366

Resource Central PO Box 11250 Overland Park, KS 66207 (913) 649-0567

Silicon Systems 14351 Myford Road Tustin, CA 92680 (714) 573-6000

Society Automotive Engineers 400 Commonwealth Drive Warrendale, PA 15096 (412) 776-4841

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Rolf K. Taylor RFD #1 Keeler Lane North Salem, NY 10560 (914) 669-5421

Trident Microsystems 205 Ravendale Drive Mountain View, CA 94043 (415) 691-9211

Voltek 100 Shepard Street Lawrence, MA 01843 (508) 685-2557

World Cogeneration PO Box 1589 Dallas, TX 75221 (214) 691-3911

Or computer local area networks?

As always, your first and foremost source of insider information in any field is in the trade journals.

As our resource sidebar for this month, I have gathered together a bunch of the more obscure and more fragmented communications trade journals for you.

I have a hunch I may have missed a few here, so be sure to let me know if you have any other favorites. A free ISMM II for your trouble.

Which mags do you use?

A Micropower Crystal Oscillator

Hacking a crystal oscillator is no big deal these days. You just bias any old CMOS gate into its active region and hang a crystal in the feedback path. But things get tricky fast if you try to run at ultra low supply currents or want to reliably start at unusually low voltages.



Hardware Hacker

Most hackers have discovered that your typical grunt CMOS transistors run out of gain at ultra low currents. And ultimately found out that the best route to micropower oscillators was to use bipolar transistors instead of CMOS gates.

Harris Semiconductor has newly introduced a cheap and very simple HA7210 all-CMOS crystal oscillator chip. It costs under a dollar and free samples are available. As figure four shows us, you simply hang a crystal on the chip, and away you go. The current is a mere five microamps at 32 kilohertz.

Pin six is an enable. Keep it high to run. Make it low to disable the chip. Pins seven and eight can program the operating current. Make them both high for low frequencies (10-100 kHz) and both low for high frequencies (5-10 MHz). Supply voltage range is 2.0 to 7.0 volts.

New Tech Lit

Some new integrated circuits for this month: The SSI 67F687 is a new engine interface peripheral offered by *Silicon Systems*. It receives gasoline engine crank and cam inputs for use

NEED HELP?

Phone or write all your US Tech Musings questions to:

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US email: *don@tinaja.com* Web page: *www.tinaja.com*

as timing and pollution management.

From *Trident*, a new *Video View* video processing chip set that offers scalable, full motion video windows and frame capture to VGA systems.

From *Hitachi*, the new HD49049FS picture-in-picture controller chip also intended for video insertion aps.

The *Grass Valley Group* has a fine video *Dictionary of Technical Terms* newly available.

A good bookstore for navigation texts and GPS satellite secrets is the *Navitech Book & Software Store*.

One source for Apple II repairs and supplies is *Rolf Taylor*.

The best Apple II magazine is still

Resource Central. And the *A2 GEnie* RoundTable has just seen its 20,000th library upload.

Yet another trade journal for this month is the *Industrial Laser Review*.

Free samples of *Volara*, *Volextra*, and *Minicel* foams are available from *Voltek*. Ask for their specifier kit.

A good source for steam calliopes is *Ragtime*. They offer a \$5 catalog.

To pick up all the fundamentals of digital integrated circuits, check my *TTL Cookbook* and *CMOS Cookbook*. The latter is now freshly republished by *Butterworth Heinemann*. It should now be stock in all major bookstores. Autographed copies are available per my nearby *Synergetics* ad.

I've just added an "automatic news group finder" as a NEWSLIST.HTML on my *www.tinaja.com* You also can find bunches of reprints here, surplus bargains, a consultant's network, and annotated hot links to lots of unusual and useful web locations.

Most of the mentioned items do appear in the *Names & Numbers* or in the *Communication Trade Journals* sidebars. Be sure to check here first before calling our US tech helpline.

Let's hear from you. \blacklozenge