There's No Turning Back

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April 8, 2002

It has been said that there are only two things in life that are certain – death and taxes. But that isn't quite true, there are actually three things in life that are certain – death, taxes and *change*.

And although it is true that history does tend to repeat itself, over the long range there is a continuing change taking place from which we can never retreat. Evolution is an obvious example of such change.

With that thought in mind, let's focus on a quantum change that has occurred to mankind over the short time span of the past two hundred years. As we develop this chronology, think of time in terms of human lifetimes – where a lifetime is, conservatively, 70 years.

We'll start with an event that happened about 200 years ago (only 3 lifetimes) in March of 1801. In that year Thomas Jefferson was sworn in as the third president of the United States. Historian Stephen Ambrose, in writing of that event stated the following:

> "*A critical fact in the world of 1801 was that nothing moved faster than the speed of a horse. No human being, no manufactured item, no bushel of wheat, no side of beef, no letter, no information, no idea, order or instruction of any kind moved faster. Nothing ever had moved any faster, and, as far as Jefferson's contemporaries were able to tell nothing ever would."*

Then the engineers and scientists in the nineteenth century applied themselves to unlocking the secrets of matter, heat and work. And in the relatively short time span of that century – through scientific observation and engineering curiosity, facilitated by a political climate of relative freedom - they developed the laws of forces, motion, thermodynamics, electricity and magnetism and gave birth to the industrial revolution.

The second snapshot is taken about a hundred years later, near the end of the nineteenth century in the year 1894 – the same year in which 16 engineers gathered in Lower Manhattan and founded the American Society of Heating and Ventilating Engineers (ASHVE), one of ASHRAE's predecessor societies. In that year, an author and playwright in London named Oscar Wilde, writing on an entirely different subject, made the statement:

> *"The fact is, civilization requires slaves . . .without slaves to do the ugly, horrible, uninteresting work culture and contemplation would become almost impossible. But human slavery is wrong, insecure and demoralizing. On* ***mechanical*** *slavery, on the slavery of the machine, the future of the world depends."*

And, about that time the engineers were shifting into high gear. During the twentieth century the engineering community created the mechanical slave indeed. The mechanical slave has served up our quality of life. The mechanical slave washes our clothes; cooks our food; cleans our dishes; moves us about over short distances or long at varying speeds, exceeding the speed of sound; provides us with untold entertainment and pleasure; stokes our fire; provides us a healthy and comfortable environment; preserves our food; operates our factories; performs our calculations; re-enforces our knowledge; keeps our records; delivers our messages anywhere in the universe at the speed of light; and provides our recreation.

That's the world we live in as we embark upon the twenty-first century; all created by technology and the engineering profession. And it's a pretty good quality of life in which culture and contemplation abound. Of the six billion people on earth, about one billion have full access to the benefits of the mechanical slave and the other five billion are certainly touched by it and are pursuing the promise.

So in a short 200 years, a quantum change has occurred in the quality of life of mankind and the change is continuing as we gather here today. And from this lifestyle totally dependent upon technology, *there's no turning back!*

But wait – the mechanical slave must be fed, and its food is the nonreplenishable energy resources of planet earth which are rapidly depleting; and its effluents are contaminating the fragile environment on which our very lives depend. And therein lies the challenge.

The greatest challenge to the human race in the twenty-first century will be to maintain and advance our quality of life as we face a dwindling reserve of energy resources and continuing environmental degradation. The situation, in a nutshell is:

1. The vast majority of the energy used to power our technology is the non-replenishable resources.

2. The energy reserves of the earth are being depleted at an exponentially increasing rate.

3. There will be a serious shortage of readily available reserves in the not-too-distant future.

4. Many of these reserves are well beyond the control of the countries that represent the largest consumers.

5. Loss of the energy to power the economy and lifestyles of the consuming countries would create an economic and social disaster of immeasurable proportion.

6. The engineering community has the ability to design machinery that uses significantly lesser amounts of energy to accomplish the same purpose. Compared to

most current practices, with no advances in technology, much less energy could be used to accomplish the same results.

7. Properly applied design philosophy will result in lower investment costs for systems that use less energy.

8. The only long-term or permanent solution is to achieve a world society based upon sustainable technology.

The scientific and engineering communities are the ones who have unlocked the secrets of nature, developed the laws of physics and chemistry, and designed the machinery and systems comprising this technology, and only the engineering community has the knowledge and the skill to solve this problem. In the twenty-first century, as we continue to provide the present quality of life and continually expand the beneficiaries thereof to include the rest of the world's population, we must turn our efforts to a solution of the energy and environmental problems.

The game plan is this:

First, we must design much more efficient energy conversion systems, be they inherently first law or second law systems.

Second, the more efficient systems must provide the same or better performance than the less efficient or wasteful systems that they replace.

Third, the more energy efficient systems must not cost significantly more than the systems they replace.

Fourth, we must employ all known laws of thermodynamics in developing systems which consume less resource energy to perform a given task.

And fifth, after we have achieved these first four objectives, we can then, and only then, turn to renewable and new sources. The reason that the first four steps must be taken first is that the renewable and new sources will be very expensive and in limited supply and not applicable to systems that are inefficient.

Now where does the heat pump fit into this plan? To answer this question, let's review briefly the fundamental laws of thermodynamics:

The Zeroth law (Figure 1) states that heat will always flow spontaneously from a region of higher temperature to one of lower temperature. From the warm sun to the cold earth; from the warm earth to the cold infinity of space, from the warm building to the cold surroundings, etc.

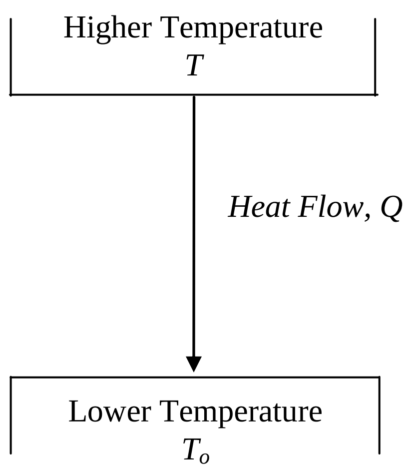
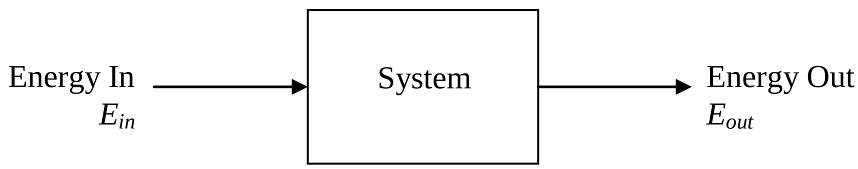


Figure 1
Zeroth Law

The First law (Figure 2) states that if we are not storing energy in a system or taking energy out of storage, then at any time all of the energy entering a system must equal all of the energy leaving the system.



$$\sum E_{in} = \sum E_{out}$$

Figure 2
First Law

The Second law is interesting. The Kelvin-Planck statement of the second law (Figure 3) is that *no engine whose working fluid undergoes a cycle can absorb heat from a single reservoir, deliver an equivalent amount of work and produce no other effect*. And the other effect is that it must reject heat to a lower temperature reservoir. Once we recognize this, of course, it all ties together. The principle that drives the heat is the zeroth law, where it is the temperature difference between the two reservoirs that drive the heat flow.

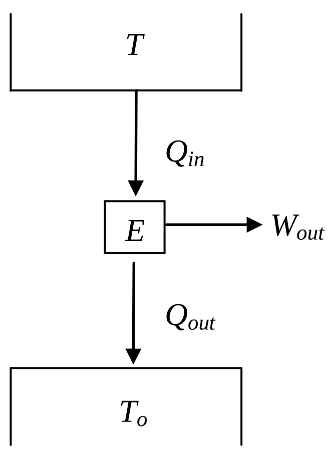


Figure 3
Second Law Heat Engine

The ratio of the work out to the heat in is called the thermal efficiency.

$$\eta_T = \frac{Work\ out}{Heat\ in}$$

And by the first law balance on the heat engine, the work is equal to the difference between the heat in and the heat out, so:

$$\eta_T = \frac{Heat\ in - Heat\ out}{Heat\ in}$$

The early thermodynamicists in the mid-nineteenth century spent a lot of time trying to figure out that if you couldn't turn all of the heat to work, how much could be converted. And the answer was discovered by a French military engineer, Nicholas Sadi Carnot, who designed a theoretically perfect engine (a reversible engine), which he called a Carnot Engine, for which the thermal efficiency was calculated to be:

$$\eta_c = \frac{T - T_o}{T}$$

where T and T_o are the absolute temperatures of the high and low temperature reservoirs respectively. This efficiency is called the Carnot efficiency, and it is the highest efficiency that any engine could ever achieve (i.e., a perfect engine) between those temperature limits.

The Clausius statement of the second law (Figure 4) is that *no machine whose working fluid undergoes a cycle can absorb heat from one reservoir, reject heat to another at a higher temperature, and produce no other effect*. This, in turn should be perfectly obvious if one believes the zeroth law, since if there were no "other effect" the heat would be flowing spontaneously from the lower to the higher temperature – a clear violation of the zeroth law.

And, of course the other effect is that external energy must be put into the cycle from either a temperature source higher than that to which the heat is being rejected or in the form of work as shown in figure 4.

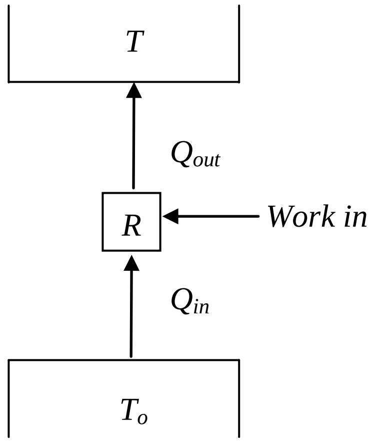


Figure 4
Second Law Refrigerating Machine
or Heat Pump

The common name for this machine is a refrigerating machine. Some research has indicated, however, that when these concepts were being developed, the earliest name for this type of machine was a heat pump because it "pumped" heat up from the lower level (temperature) reservoir at temperature T_o to the higher level reservoir at temperature T.

The next obvious question to be asked, of course, is "how much work does it take to move a given amount of heat out of the low temperature reservoir?" (This is called the "Heat in" or the "refrigerating effect.") And that is classically expressed as the "coefficient of performance" of the refrigerating machine where:

$$CP = \frac{Refrigerating\ Effect}{Work\ in} = \frac{Q_{in}}{W}$$

Performing a first law balance on the machine, it is seen that the Heat out is equal to the sum of the Heat in and the work, so the coefficient of performance can be expressed as:

$$CP = \frac{Q_{in}}{Q_{out} - Q_{in}}$$

The next obvious question would be, "what would be the most refrigerating effect we could get for a given unit of work in?", or another way to ask would be, "what would be the least amount of work required to get a given amount of refrigerating effect?" The answer would be expressed, of course, as the machine with the highest coefficient of performance.

The nineteenth century investigators then went about trying to figure out what would be the highest *CP* that could be achieved, and, again, Sadi Carnot developed the answer by designing a theoretical or "ideal" refrigerating machine (the Carnot Refrigerating Machine) for which he proved that the coefficient of performance was:

$$CP_c = \frac{T_o}{T - T_o}$$

where again, T and T_o are the absolute temperatures of the high and low temperature reservoirs respectively.

If the purpose of the machine were to provide heat to the high temperature reservoir instead of removing heat from the low temperature reservoir, the effectiveness was expressed by the heating coefficient of performance:

$$HCP = \frac{Heat\ Rejected}{Work}$$

And the Carnot *HCP* is found to be:

$$HCP_c = \frac{T}{T - T_o}$$

Note, if the higher temperature goes up or the lower temperature goes down, the Carnot *CP* and *HCP* get smaller. But a reduction in the lower temperature will decrease it more than an equal increase in the higher temperature in either case.

If we perform a simple first law balance on the refrigerating machine, it's obvious that, in consistent units, the heat being rejected (the heating effect) is greater than the external energy input because it is equal to the sum of the external energy plus the refrigerating effect. To put some values to this, the best possible machine would be the Carnot machine where, between a low temperature of, say, 0ºC and a high temperature of 32ºC, the *HCP* would be:

$$HCP_c = \frac{305}{305 - 273}$$

$$HCP_c = 9.53$$

Thus, ideally, we could get almost 10 times as much heat out as the equivalent of the work that we put in!

To the nineteenth century engineers, this was more an academic observation than anything else because, except for a mill which produced work from flowing water or the wind, the only way they had for making work was with a steam engine and, in doing so, they suffered all of the losses of that second law Carnot prediction plus friction and departure from ideal conditions. And besides, they used heat to drive the engine, and the heat could be used directly by a simple first law process with nothing but combustion and stack losses.

However, with the advent of commercial electric power, there was a new awareness of the concept of the heat pump, and several attempts were made at using heat pumps driven by electric motors in the 1930's. Most of these tried to pump heat from constant temperature well water to heat buildings or industrial process that didn't require very high temperatures. However, the market was limited, and the technology in materials and machinery was such that reliable machines were prohibitively expensive.

But with the advent of space cooling or air conditioning, the same machine could be used for both heating and cooling by "reversing the cycle." This meant that the cost of the basic refrigerating components could be amortized for both the heating purposes and the cooling purpose which, compared to cooling only, increased the load annual factor from 12% to 30% and significantly improved the economics. These early machines were called reverse cycle heating/cooling units.

In the 1950's and 60's, several manufacturers in the United States offered reverse cycle units, or heat pumps, for heating commercial buildings. These devices usually used the ambient environment for the heat source. An obvious disadvantage in this concept is that as it gets colder outdoors, more heat is needed, and at the same time, the unit is becoming less and less effective (Carnot).

Our firm, in the late 50's and through the 60's, designed a series of buildings in Southeast Missouri where there was a large aquifer less than 20 feet below the surface. We designed heat pumps which used the well water as a heat source, drove the refrigerating compressors with natural gas engines, and salvaged heat off of the engines to supplement the pumped heat. These systems realized about 1,800 BTU of heat to the building for every 1,000 BTU of natural gas burned, or 180% thermal (first law) efficiency. Had the gas been burned in a boiler, the best that could have been achieved would have been about 75% to 80%.

Then the internal source heat pump was introduced which incorporates a circulating water system combined with heat pumps to extract heat from the areas of the building that have an over-abundance (thereby cooling those spaces) and move it to the areas which need heat. Since the balance is not always perfect, these systems generally include devices that can add or remove first law heat to the "heat pump" circuit.

So, as we assemble here today, the technology in materials and machinery has enabled us to once again revisit the benefits observed by the engineers and scientists a hundred and fifty years ago, only now we have the wherewithal to take advantage of the technology, thanks to improvements in materials and machinery and the advent of air conditioning.

Now let's return to our energy game plan. Certainly one of the renewable energy sources we have and will have to power buildings is electricity provided by nature's forces. Two currently available renewable commercial sources are wind power and hydro power. A kilowatt of electricity could provide approximately 3,413 BTU per hour of heat if simply converted through an electrical resistance. However, when used to drive a heat pump with a well water source the same kilowatt might provide as much as 12,000 BTU per hour.

And that brings us to the purpose of this conference. To summarize, the greatest challenge to the engineering community in the 21^{st} century is to continue to provide our quality of life and to bring it to the other five billion people on earth as we face a dwindling supply of nonrenewable energy resources. Building environmental systems represent about 30% of the world's consumption, and the heat pump certainly provides a here-and-now technology to shift a good portion of that energy to a renewable source.

It's appropriate that this conference is being held here in Beijing in the People's Republic of China, where they are currently working on the construction of a dam on the Yangtze River that will be part of the largest renewable energy system in the world.

No, there's no turning back. And as we move forward, the heat pump, which has fascinated engineers for the past one hundred and fifty years will certainly "come into its own."

As we attend these excellent sessions during the next three days, we will learn of the latest technology and concepts in the science of heat pumps.

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July 1, 2001

WILLIAM J. COAD

Abbreviated Biography

William J. Coad, P.E., President of ASHRAE and Principal and immediate past Chairman and CEO of McClure Engineering Associates has forty-three years experience in the design, installation and management of HVAC and refrigeration systems. He served for twenty-nine years as a lecturer and affiliate professor of mechanical engineering at Washington University where he taught graduate level courses and served as thesis advisor in indoor environmental systems design. He is also on the Board of Directors of Mestek Corporation of Pittsburgh and Exergen Corporation of Boston.

Mr. Coad has authored one book and over one hundred articles and papers on various aspects of building systems engineering, was the principal author of Chapter 12 in the ASHRAE Systems Handbook and a co-author of the book “Principles of HVAC” published by ASHRAE and author of the ASHRAE PDS-1 Air Systems Design for Energy/Cost Effectiveness. He and his firm have been pioneers in the development of computer programs for building energy analysis, cogeneration systems, well water source heat pumps, one-pipe chilled water systems, and variable flow chilled water systems. He has been widely recognized for his contributions in advancing the state-of-the-art, is an ASHRAE Fellow and recipient of the ASHRAE Crosby Field Award, the Louise and Bill Halliday Distinguished Fellow Award, the award for Best Journal Article, the F. Paul Anderson Award, and the Alumni Achievement Award of Washington University.