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A Tribute to Energy Systems Scientists and Engineers

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As members of the Energy Systems Division of the ASME, we must be very proud of, grateful to, and challenged by the achievements of colleagues over the past two and a half centuries. Their ingenuity, and creativity contributed to the development of energy processing machines that radically changed and continue to change the world, machines of higher and higher efficiency, and lower and lower cost for industrial applications; for locomotion on land, on and in the sea, and in the air; for the generation of electricity; and for powering other necessities of life. So far, the work is unquestionably outstanding but by no means complete. Much remains to be done both in understanding the scientific foundations, and in extending and improving the applications. My strong feeling and expectation is that current and future generations of scientists and engineers will continue to rise to the challenge, and make even greater theoretical and practical contributions.

The pioneers started without the benefit of any systematic body of theoretical knowledge, and built coal-fired plants that yielded a very small amount of shaft energy per bushel of coal, that is, plants that were very inefficient. Over a period of 70 years, however, they increased that ratio by a factor of 20 as shown in *Figure 1*. Said differently, by using today's terminology, they started with heat engines that had a thermal efficiency of about one half of one percent, and increased it to about 10 percent, as shown in *Figure 2*.

In 1824, this dramatic improvement in efficiency of heat engines attracted the attention of Sadi Carnot, a twenty-eight year old Frenchman who had studied at the Sorbonne, the Collège de France, and the École des Mines. He said (Carnot, 1960): "The question has often been raised whether the motive power of heat[†] is unbounded, whether the possible improvements in steam engines have an assignable limit – a limit by which the nature of things will not allow to be passed by any means whatsoever, or whether, on the contrary, these improvements may be carried on indefinitely. …In order to consider in the most general way the principle of the production of motion by heat, it must be considered independently of any mechanism or any particular agent. It is necessary to establish principles applicable not only to steam engines but to all imaginable heat engines, whatever the working substance, and whatever the method by which it is operated. …Machines which do not receive their motion from heat, those which have for a motor the force of men or of animals, a waterfall, an air current, etc., can be studied even to their smallest details by the mechanical theory. All cases are foreseen, all imaginable movements are referred to these general principles, firmly established, and applicable under all circumstances. This is the character of a complete theory. A similar theory is evidently needed for heat engines. We shall have it only when the physics shall be extended enough, generalized enough, to make known beforehand all the effects of heat acting in a determined manner on any body."

[†] By motive power of heat he meant "useful effect that a motor is capable of producing. This effect can always be likened to the elevation of a weight to a certain height. It has, as we know, as a measure the product of the weight by the height to which it is raised".

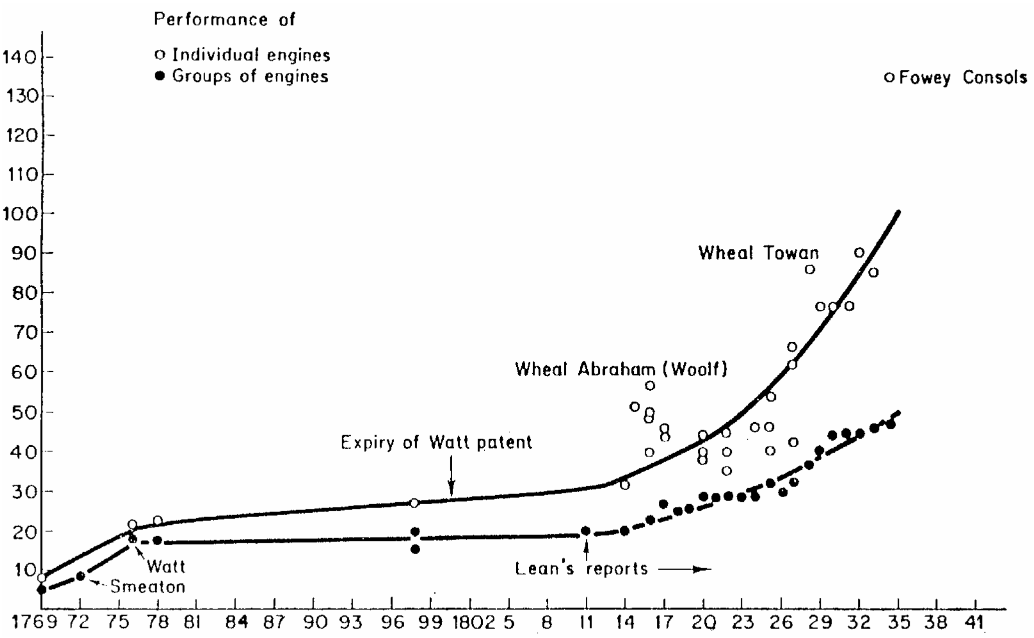

Figure 1. Change of shaft energy per bushel of coal of steam-powered engines from 1769 until 1835 (Cardwell, 1971).

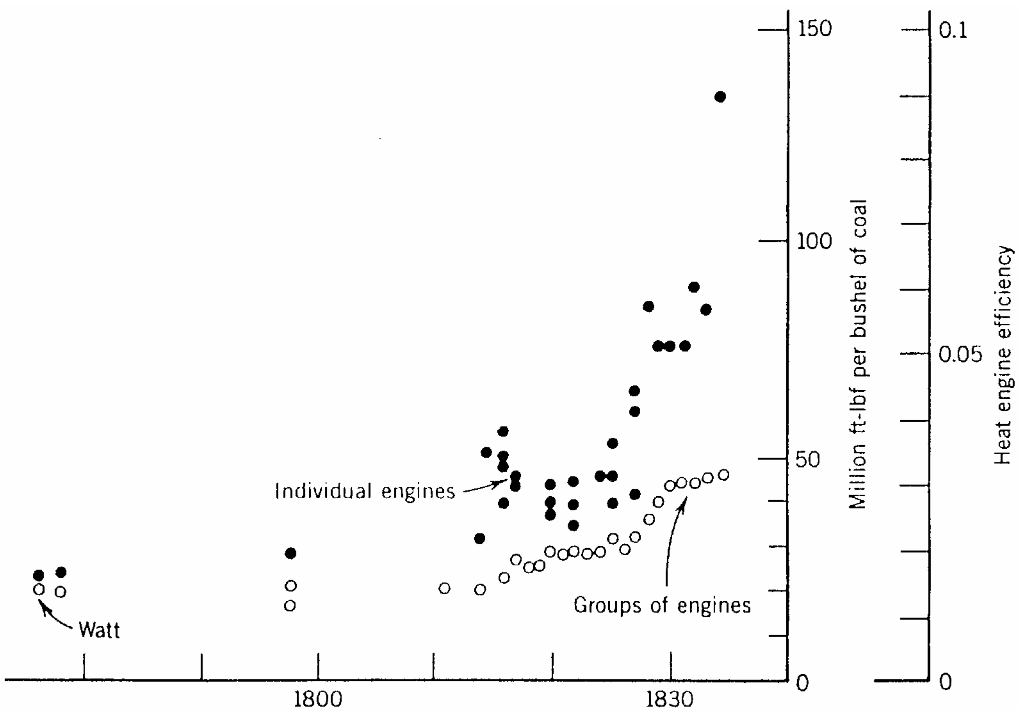

Figure 2. The same data as in Figure 1, including a calculated thermal efficiency (Bejan, 1988).

Carnot (1960) concludes his "Reflections on the motive power of fire" with the following remarks: "We should not expect ever to utilize in practice all the motive power of combustibles The attempts made to attain this result would be far more hurtful than useful if they caused other important considerations to be neglected. The economy of the combustible is only one of the conditions to be fulfilled in heat engines. In many cases it is only secondary. It should often give precedence to safety, to strength, to the durability of the engine, to the small space which it must occupy, to small cost of installations, etc. To know how to appreciate in each case, at their true value, the considerations of convenience and economy which may present themselves; to know how to discern the more important of these which are only secondary; to balance them properly against each other, in order to attain the best results by the simplest means; such should be the leading characteristics of the man called to direct, to coordinate the labors of his fellow men, to make them cooperate towards a useful end, whatsoever it may be".

I include these lengthy quotations from Carnot's Memoir for three reasons. First, because they express his strongly felt conviction that heat engines are part of fundamental physics. Second, because they challenge the visionary creativity of all scientists and engineers to extend and generalize the physics in order to include the effects of heat. And third, because they show that Carnot was the first true thermo-economist, in addition to conceiving the seminal ideas of thermodynamics!

Though almost two centuries have passed, it is noteworthy that only a small number of scientists and engineers have imaginatively and creatively responded to Carnot's profound understanding of the problem, that is, that heat engines are part of fundamental physics.

On the basis of arguments that, in retrospect, are not completely and unambiguously defined, Carnot tried to respond to his own challenge, and discovered a fundamental result – theorem – of the still missing generalized theory of physics. He said: "The motive power of heat is independent of the agents employed to realize it; its quantity is fixed solely by the temperatures of the bodies between which is effected, finally, the transfer of the caloric".

Despite the fact that some of Carnot's arguments are ill-defined, we can, on the basis of the hindsight of the many decades that have gone by, assert that his result is absolutely correct and irreplaceable. Recent claims to the contrary not withstanding, to this date no other limit has or can be defined because no such alternative exists under the conditions specified by Carnot. This is a most important conclusion which we should not overlook as we try to charter future developments.

Following Carnot's seminal ideas, three important contributions advanced the understanding of heat engines, and facilitated the continuation of the improvement of their performance. The first is the introduction of the pressure versus volume diagram of the working fluid of an engine operating between two bodies, one at high temperature and the other at low temperature (Clapeyron, 1834). This diagram can be obtained experimentally by measurements, as the working fluid undergoes a cyclic change of state.

From analyses of such diagrams, Clapeyron concludes that: (a) "If the quantity of heat[†] communicated by the hot body equals the heat communicated by the cold body, then the resulting mechanical action can be used in a duplicate engine to pump the same amount of heat from the cold body to the hot body[††]; and (b) the quantity of mechanical action plus the quantity of heat[†††] that can pass from the hot body to the cold body are quantities of the same nature, and it is possible to replace the one by the other. This replacement is the same as in mechanics where a body which is able to fall a certain height and a mass moving with a certain velocity are quantities which can be transformed one into the other by physical means".

It is noteworthy that this important conclusion is an unambiguous statement of one form of the energy balance which is a theorem of both the (correct) first and second laws of thermodynamics, and which unfortunately practically every scientist and engineer, and practically every textbook on either physics or thermodynamics call the first law of thermodynamics (Gyftopoulos and Beretta, 1991).

The second important contribution is the establishment of an absolute scale for temperature by William Thomson (Lord Kelvin) (Thomson, 1882). He observed that Clapeyron used an unnecessarily complicated argument and suggested that Carnot's result about the motive power $d\dot{W}$ of the heat rate $\dot{Q}$ could be written in the form

$$\frac{d\dot{W}}{\dot{Q}} = \frac{dt}{C(t)} \tag{1}$$

where $C(t)$ is a function of the empirical temperature t that must be determined by experiments. As a result of this observation, Kelvin made the important discovery that $C(t)$ can be used to define a new, absolute scale of temperature "independent of the properties of any particular matter" by means of the relation

$$T = C(t) \tag{2}$$

Accordingly, Eq. (1) can be expressed in the forms

$$\frac{d\dot{W}}{\dot{Q}} = \frac{dT}{T} \quad \text{or} \quad \frac{\dot{W}}{\dot{Q}} = \frac{T_1 - T_2}{T_1} \tag{3}$$

[†] Of course, on the basis of our current understanding of thermodynamics, "heat" must be taken to mean "entropy".

[††] Today we would say that both the process and its inverse are reversible.

[†††] Here heat stands for energy.

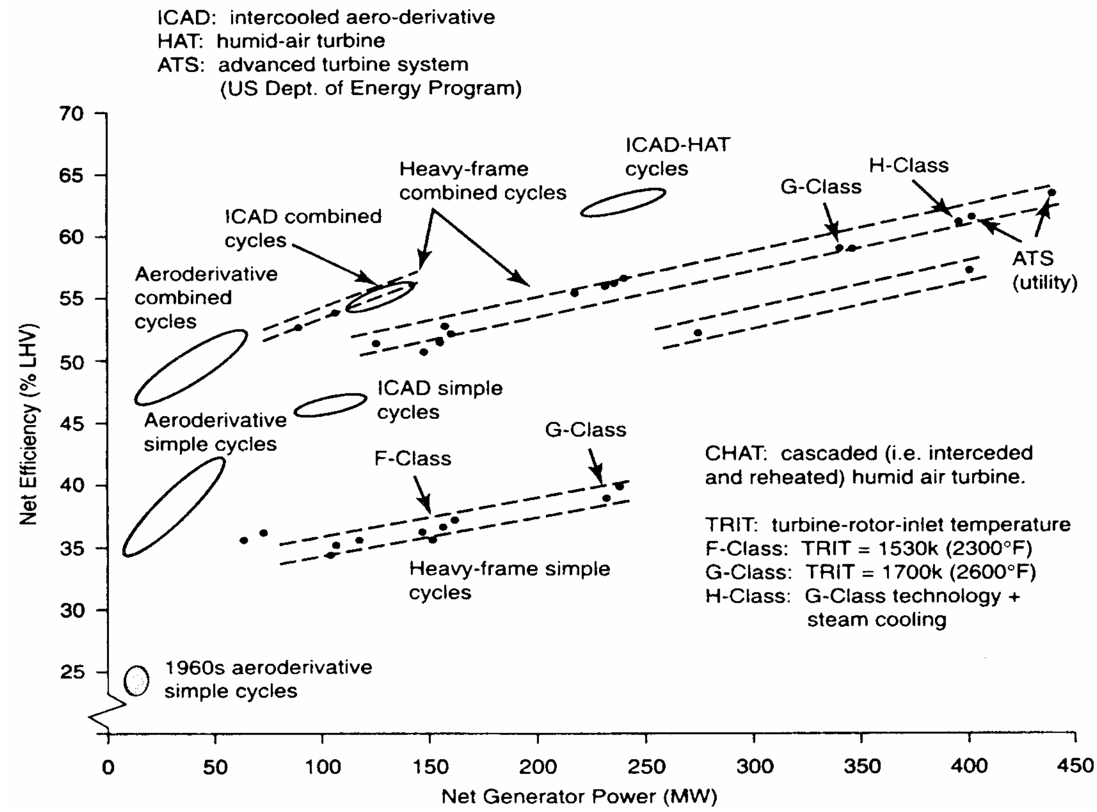

Figure 3. Thermal efficiency versus power of different turbines and combined cycles (Wilson and Korakianitis, 1998).

We are now in the 1850's and still a clear understanding of the physics of thermo-dynamics is lacking. This deficiency was partly overcome by two important and trailblazing contributions by Clausius (Kestin, 1976). He recognized the concept of entropy – the concept that distinguishes thermo-dynamics from mechanics – and the energy and the entropy balances, two balances that are both cornerstones of all thermodynamic analyses and theorems of the unambiguous, noncircular, and well defined statements of the first, second, and third laws of thermo-dynamics (Gyftopoulos and Beretta, 1991).

A striking consequence of the correct application of these balances is that the one and only upper thermodynamic limit of any process is the reversible process. In certain cases, irreversible processes may be unavoidable because of capital, material, and labor considerations or lack of creative imagination for reducing the entropy generated by irreversibility but not because of any thermodynamic principles.

So, what has been happening over the past century and a half? A customer goes to a manufacturer and says: I wish to have a power plant for so many units of power. Build me such a plant at the lowest cost per unit power, and the highest power per unit of fuel rate. And remarkably and admirably, engineers use their ingenuity and creativity and satisfy the requests of their customers by continuously decreasing both the cost, and the fuel rate or, equivalently, increasing the efficiency.

Let us now look at the results of these interactions between customers and manufacturers. The improvement of the thermal efficiency of land based turbines is illustrated by the experimental data in *Figure 3*. It is clear that the higher the power, the higher the thermal efficiency. In fact it is interesting to estimate the thermodynamic efficiency of heavy-frame, combined cycle turbines. As is well known, about 30% of the availability (exergy) of the heating value of a hydrocarbon is lost in the course of combustion. An illustrative example is shown in *Figure 4*. If we do not charge this loss to the performance of the combined cycle gas turbine, then the largest thermodynamic efficiency that has been achieved to date (i.e. the ratio of the thermal efficiency over the availability of the products of combustion at the entry of the power plant as a fraction of the heating value of the fuel) is about 0.63/0.70 = 0.9 or 90%! This is a remarkable achievement, which illustrates the impressive progress that has been made over the past century and a half.

The improvement in specific fuel consumption (which is proportional to the inverse thermal efficiency) versus the output power of marine turbines is shown in *Figure 5*. It is clear that the higher the power rating, the lower the specific fuel consumption or, equivalently, the higher the thermal efficiency.

The improvement in efficiency of internal combustion engines (Sulzer Diesel, direct injection DI, indirect injection IDI, and spark ignition SI) is shown in *Figure 6*. The higher the displacement (power) is, the higher the efficiency (breaking power).

The continuous improvement of performance of aircraft engines – the higher the power, the higher the efficiency – is illustrated by the data in *Figures 7 and 8*, including anticipated improvements during the present decade.

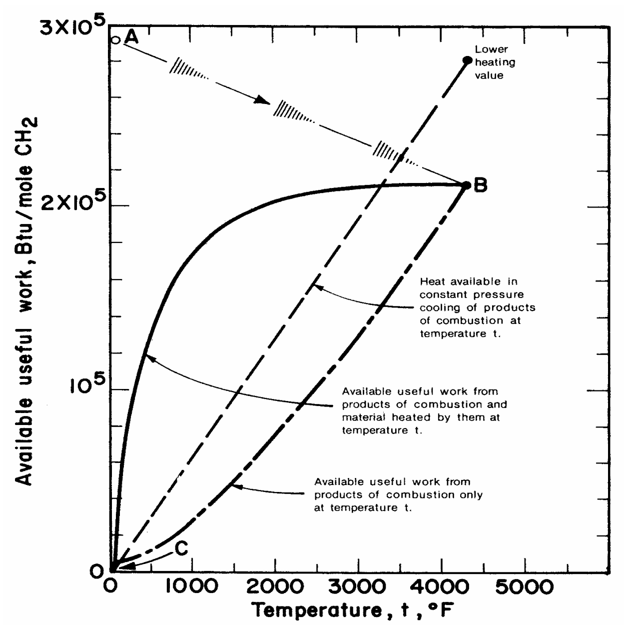

Figure 4. Available useful work (availability or exergy) versus temperature from the products of combustion of a hydrocarbon (Gyftopoulos et al., 1974).

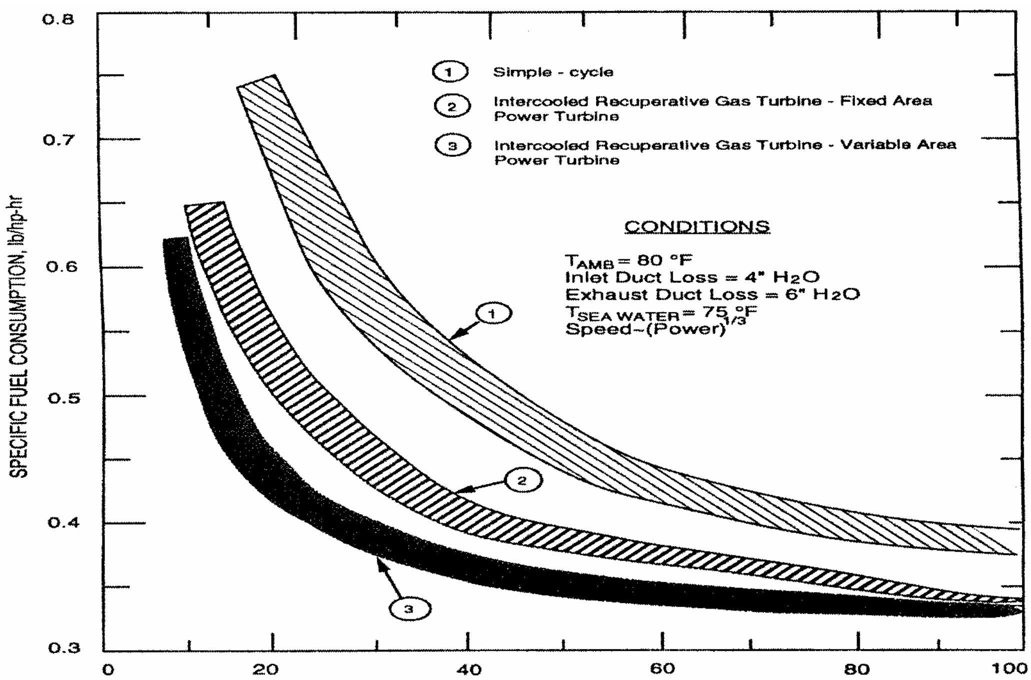

Figure 5. Specific fuel consumption (inverse thermodynamic efficiency) versus power of marine turbines (Groghan, 1992).

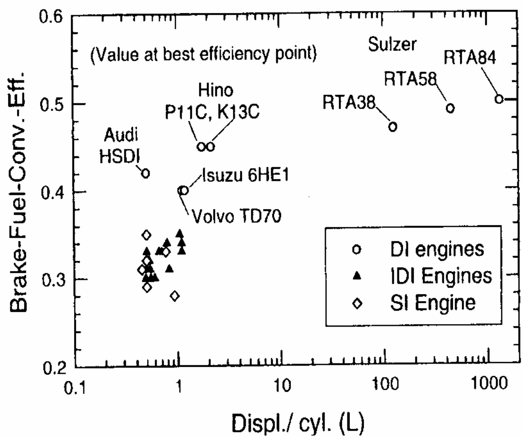

Figure 6. Thermal efficiency versus the shaft energy of internal combustion engines (Cheng, 2001).

Finally, experimental results of power output and thermal efficiency versus the emitter temperature of thermionic converters are shown in *Figure 9*. It is clear that the higher the power of the thermionic converter, the higher the thermal efficiency.

Over the past five decades, a large group of colleagues have flooded the scientific and engineering literature with publications that claim to have discovered a new thermodynamics, i.e. finite-time thermodyna-mics (FTT), which accounts for unavoidable irreversibilities. The proponents of FTT claim that the maximum power of a heat engine operating between two reservoirs at temperatures T_1 and T_2 is obtained at a thermal efficiency of

$$\eta_{CA} = 1 - (T_2/T_1)^{1/2} \tag{4}$$

and not at the Carnot thermal efficiency of

$$\eta_C = 1 - (T_2/T_1) \tag{5}$$

They argue that, in order to achieve the Carnot efficiency, the engine must operate at an infinitesimal rate or, equivalently, at zero power output (*Figure 10*).

A large number of fundamental theoretical considerations plus many experimental results (Gyftopoulos, 1997, 1999, 2000; Gyftopoulos et al., 1994) prove beyond a shadow of a doubt that there does not exist and cannot exist any such theory as FTT. I am convinced that it is important to heed Carnot's seminal idea and make an extra effort to really understand the *physics* of the science of thermodynamics because such understanding will help us continue improving the outstanding results achieved by our predecessors. To do so we must not fall into the trap that was brought to my attention by my coworker and close friend Professor von Spakovsky. It is a trap described by the famous physicist Arnold Sommerfeld who said: "The first time I studied thermodynamics, I thought I understood it except for a few minor points. The second time, I thought I did not understand it except for a few minor points. The third time, I knew I did not understand it, but it did not matter, since I could still use it effectively".

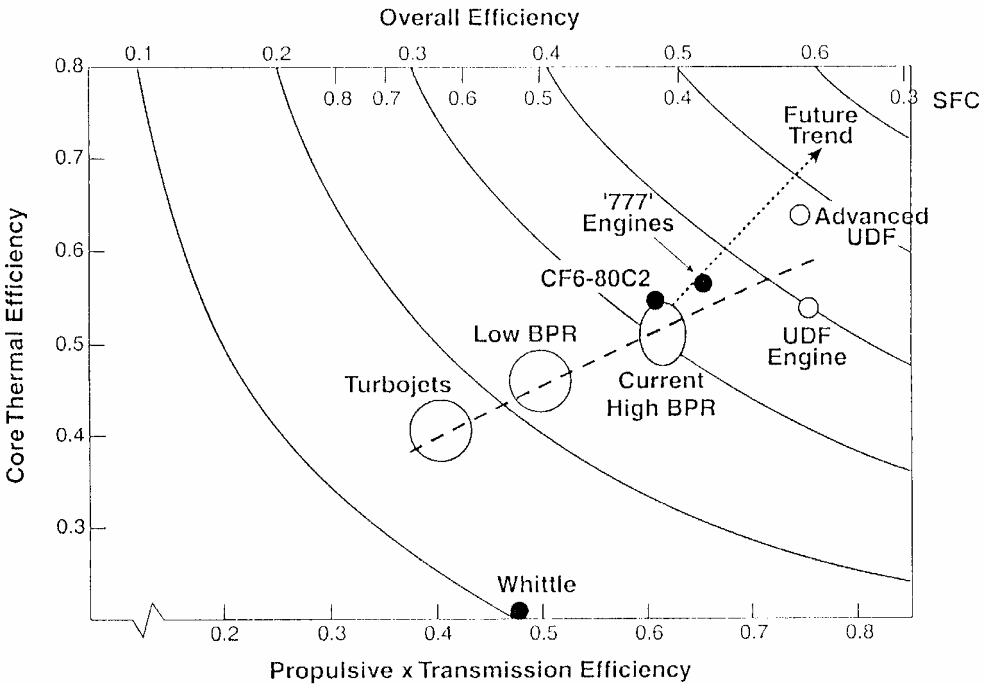

Figure 7. Core thermal efficiency versus propulsive × transmission efficiency of aircraft engines (Koff, 1991).

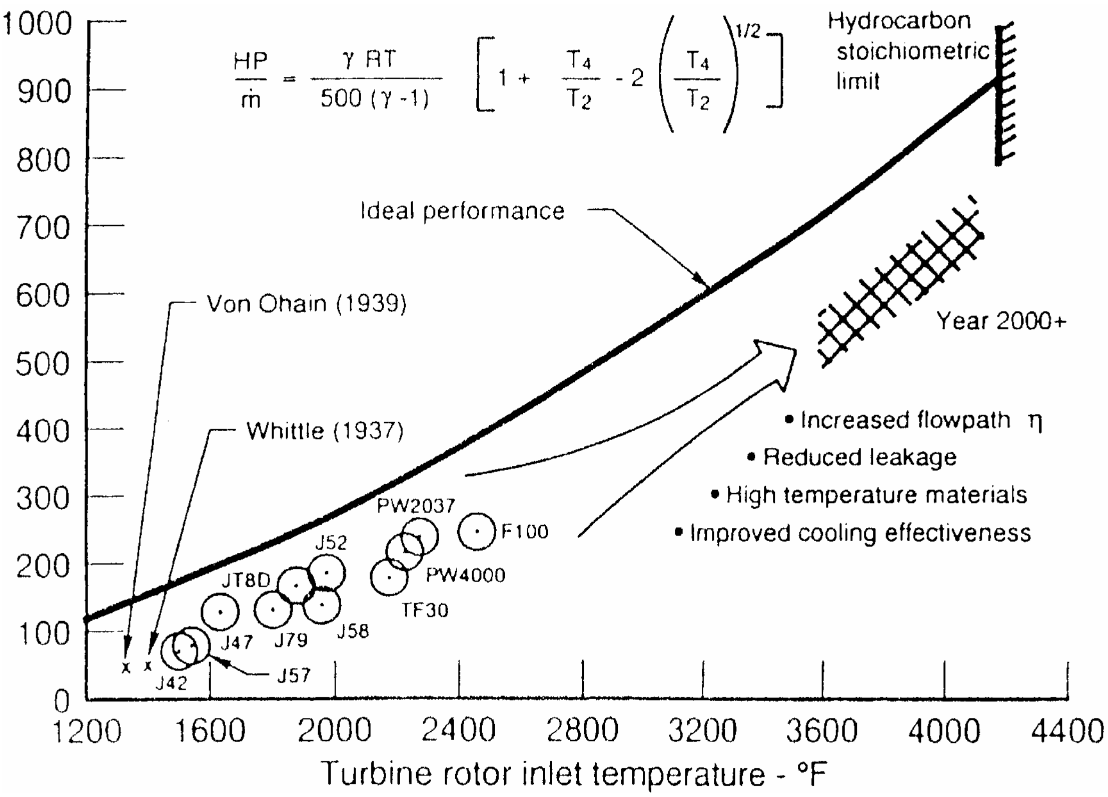

Figure 8. Horsepower versus turbine rotor inlet temperature (Koff, 1991).

It seems to me that the challenge and the rewards lie outside what we can presently use effectively. For example, how about trying to design machines that pass through states that are not thermodynamic equilibrium? If we could, then we would be working with systems that have larger initial availability (exergy). As a simple (perhaps naïve) illustration of this idea, consider the energy versus entropy diagram of a system with fixed amounts of constituents **n** and fixed volume V. If the states of such a system are projected on an energy versus entropy plane, then they are found to lie in the cross-hatched area of *Figure 11.* For given energy, the thermodynamic equilibrium state is A_0, and its availability with respect to a reservoir at temperature T is represented by the vertical distance of A_0 from the tangent of the E versus S curve at the point where the slope is T. On the other hand, if, for the same energy, the initial state of the system is not thermodynamic equilibrium, then the availability (left dotted vertical line) is much larger than that of A_0. An existing device that satisfies this idea is a charged electricity storage battery.

In closing, I hope you agree with me that we owe a unanimous vote of thanks and gratitude to the energy systems engineers that preceded us for their remarkable accomplishments, and a promise that we will make every effort to understand the beautiful and powerful subject of thermodynamics so that we can continue the productive tradition established by the pioneers.

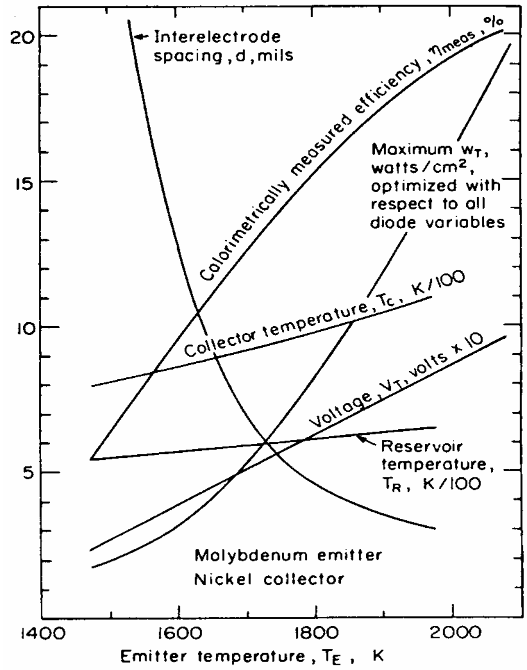

Figure 9. Power output and measured thermal efficiency versus emitter temperature of fully optimized thermionic energy converters (Hatsopoulos and Gyftopoulos, 1973).

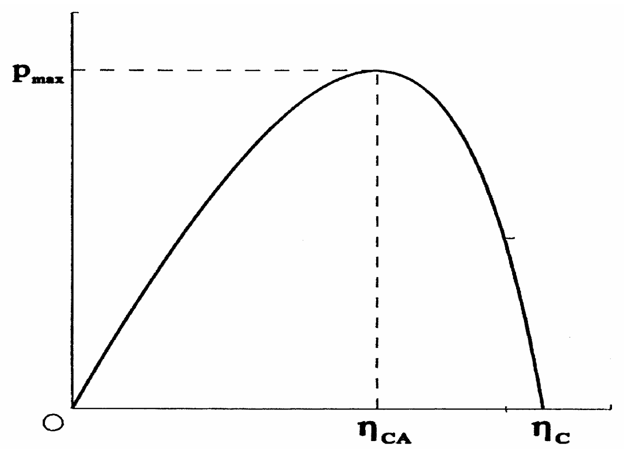

Figure 10. Power versus efficiency according to finite time thermodynamics (Chen et al., 2001).

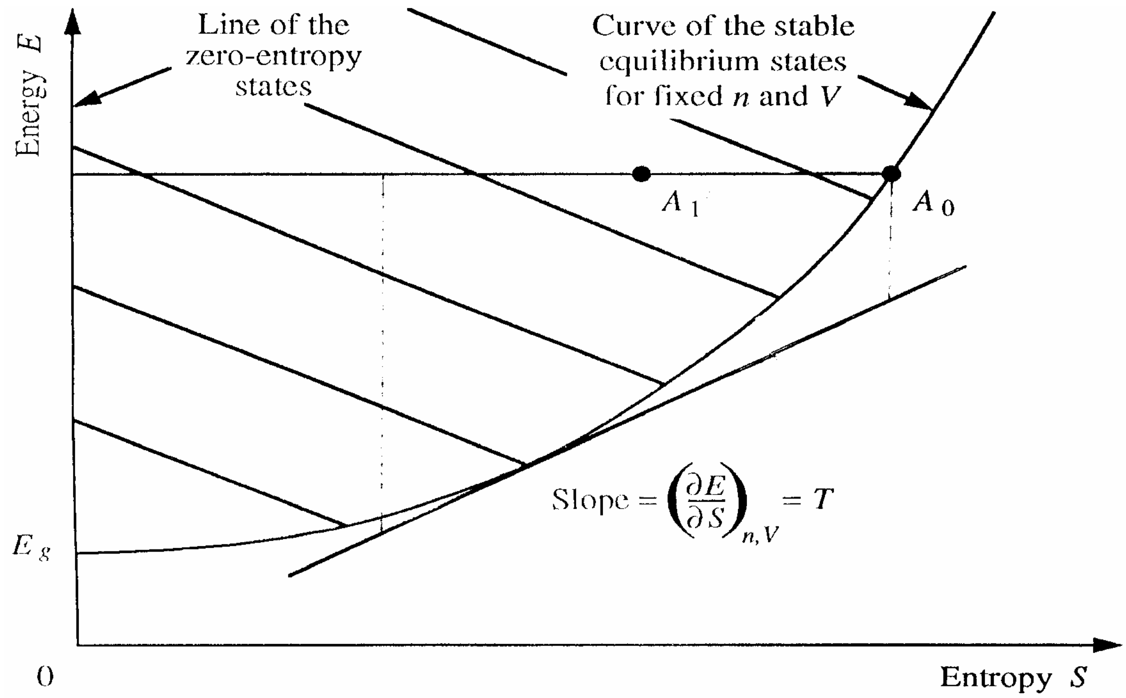

Figure 11. Projection of the multidimensional property space on an energy versus entropy plane for a system with amounts of constituents, and fixed volume (Gyftopoulos, and Beretta, 1991).

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