The following is taken from the book *The Second Law*, by Henry A. Bent (Oxford University Press, New York, 1965) first edition, p.59ff.

Sadi Carnot

In the daily events of life, energy is never created and it is never destroyed. It is only transformed. Through gentle metabolic processes, a day laborer gradually transforms the chemical energy of the food he eats and the oxygen he breathes into heat, sound, and useful work. Through more violent processes, a jet engine during take-off rapidly transforms chemical energy into heat, sound, kinetic energy, and (hopefully) potential energy. In a few seconds a jet engine transforms more energy than can be transformed by a day laborer in many days. Jets, to use a technical term, are more *powerful* than day laborers.

Civilizations are often characterized by the power of their energy converters. The shorter the time required to transport a cargo across a continent, or to flatten a city, the more advanced the civilization is said to be.

Man's first energy converter was man. Later draft animals were used; then steam engines. Today (1965) man's principal energy converters are internal combustion engines, jet engines, and rockets.

In ancient times, societies that domesticated draft animals enjoyed two distinct advantages over simpler, food gathering societies. Animals such as horses and oxen can convert directly to useful mechanical-work the energy of grasses, which man himself cannot, and these animals are more powerful than men. Thus, when time was precious, as often it was during the spring planting season, draft animals, though usually less efficient than man in converting plant energy to mechanical energy, proved to be worth their keep.

By the nineteenth century, however, a more powerful and more versatile energy converter was being developed, and draft animals were becoming obsolete. The transition from horses and oxen, which had been used by mankind for thousands of years, to the newer energy converter did not occur quickly, however, and the nation where the newer, more powerful converter was first widely used enjoyed for the better part of a century a signal advantage over her sovereign rivals. That nation was England. Her advantage was the steam engine, the most perfect device then known to man for rapidly converting to useful work anything that would burn. With the steam engine, England could keep dry her deepening coal mines from which came the coal to make the coke to stoke the furnaces of the converters that made the iron from which were fashioned the hulls of the ships of the British navy and the tools of the Industrial Revolution.

Improvements in the steam engine came slowly at first, by trial and error and occasional success, for no one understood what factors determined the motive-power of heat, until this problem was examined in a deeply fundamental and strikingly original manner by a young French military engineer, Sadi Carnot.

Around 1820, when he was twenty-three or twenty-four years old, Carnot published privately a brochure titled Reflections on the Motive-Power of Heat, and on Machines Fitted to Develop that Power. In this brochure, neglected until the Englishman William Thomson recognized its full merits in 1848, Carnot showed that the maximum efficiency of a steam engine is determined by the temperature of its boiler and the temperature of its condenser.

Below is a brief digest of Carnot's brochure. This brochure turned the art of making heat engines into a science and laid the foundations for the Second Law of Thermodynamics. [1]

Everyone knows that heat can produce motion. That it possesses vast motive- power no one can doubt, in these days when the steam-engine is everywhere so well known. The study of these engines is of the greatest interest, their importance is enormous, their use is continually increasing, and they seem destined to produce a great revolution in the civilized world.

The most signal service that the steam-engine has rendered to England is undoubtedly the revival of the working of the coal-mines, which had declined, and threatened to cease entirely, in consequence of the continually increasing difficulty of drainage, and of raising the coal. We should rank second the benefit to iron manufacture. To take away today from England her steam-engines would be to take away at the same time her coal and iron. It would be to dry up all her sources of wealth, to ruin all on which her prosperity depends, in short, to annihilate that colossal power.

If the honor of the discovery of the steam engine belongs to the nation in which it has acquired its growth and all its developments, this honor cannot be here refused to England. But notwithstanding the work of all kinds done by steam-engines, notwithstanding the satisfactory condition to which they have been brought today, their theory is very little understood, and the attempts to improve them are still directed almost by chance.

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 which the nature of things will not allow to be passed by any means whatever; or whether, on the contrary, these improvements may be carried on indefinitely. We propose now to submit these questions to a deliberate examination.

The phenomenon of the production of motion by heat has not been considered from a sufficiently general point of view. 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.

The production of motion in steam-engines is always accompanied by a circumstance on which we should fix our attention. This circumstance is the re-establishing of equilibrium in the caloric; that is, its passage from a body in which the temperature is more or less elevated, to another in which it is lower. The steam is here only a means of transporting the caloric.

The production of motive power is then due in steam-engines not to an actual consumption of caloric, but *to its transportation from a warm body to a cold body.* According to this principle, the production of heat alone is not sufficient to give birth to the impelling power: it is necessary that there should also be cold; without it, the heat would be useless.

Wherever there exists a difference of temperature, it is possible to have also the production of impelling power. Steam is a means of realizing this power, but it is not the only one. All substances in nature can be employed for this purpose, all are susceptible of changes of volume, of successive contractions and dilatations, through the alternation of heat and cold. All are capable of overcoming in their changes of volume certain resistances, and of thus developing the impelling

[1] There has been some discussion as to what Carnot meant by the term "caloric." Early writers supposed that he meant "heat." In a footnote Carnot says that he employs the two expressions indifferently. In certain passages the term we would use today is "entropy."

power. A solid body – a metallic bar for example – alternately heated and cooled increases and diminishes in length, and can move bodies fastened to its ends.

It is natural to ask here this curious and important question: Is the motive power of heat invariable in quantity, or does it vary with the agent employed to realize it as the intermediary substance, selected as the subject of action of the heat?

We take, for example, one body A kept at a temperature of 100° and another body B kept at a temperature of 0°, and ask what quantity of motive power can be produced by the passage of a given portion of caloric (for example, as much as is necessary to melt a kilogram of ice) from the first of these bodies to the second. We inquire whether this quantity of motive power is necessarily limited, whether it varies with the substance employed to realize it, whether the vapor of water offers in this respect more or less advantage than the vapor of alcohol, of mercury, a permanent gas, or any other substance.

Carnot began his analysis by noting that a heat engine can be run in reverse.

Whenever there exists a difference of temperature, motive-power can be produced. Reciprocally, whenever we can consume this power, it is possible to produce a difference of temperature.

This led Carnot to the idea of a reversible ("Carnot") cycle, which he twice described, first in general terms and later in specific detail. Between these two descriptions Carnot presented this interesting observation:

By our first operations there would have been at the same time production of motive power and transfer of caloric from the body A to the body B. By the inverse operations there is at the same time expenditure of motive power and return of caloric from the body B to the body A. But if we have acted in each case on the same quantity of vapor, if there is produced no loss either of motive power or caloric, the quantity of motive power produced in the first place will be equal to that which would have been expended in the second, and the quantity of caloric passed in the first case from body A to the body B would be equal to the quantity which passes back again in the second from the body B to the body A; so that an indefinite number of alternative operations of this sort could be carried on without in the end having either produced motive power or transferred caloric from one body to the other.

Following directly upon this observation is one of the most pregnant observations in the history of thermodynamics.

Now if there existed any means of using heat preferable to those which we have employed, that is, if it were possible by any method whatever to make the caloric produce a quantity of motive power greater than we have made it produce by our first series of operations, it would suffice to divert a portion of this power in order by the method just indicated to make the caloric of the body B return to the body A from the refrigerator to the furnace, to restore the initial conditions, and thus to be ready to commence again an operation precisely similar to the former, and so on: this would be not only perpetual motion, but an unlimited creation of motive power without consumption either of caloric or of any other agent whatever. Such a creation is entirely contrary to ideas now accepted, to the laws of mechanics and of sound physics. It is inadmissible. We should then conclude that *the maximum of motive power resulting from the employment of steam is also the maximum of motive power realizable by any means whatever.*

This conclusion is sufficient, William Thomson showed, to define a temperature scale that is independent of the specific properties of substances. Thomson called it the *absolute temperature* scale. It is, we have seen, the key to the uses of the Second Law.

Carnot also established the following conclusions:

The necessary condition that the motive power of a heat engine be a maximum is *that in the bodies employed to realize the motive power of heat there should not occur any change of temperature which may not be due to a change of volume.* Reciprocally, every time that this condition is fulfilled the maximum will be attained. This principle should never be lost sight of in the construction of heat-engines ; it is its fundamental basis. If it cannot be strictly observed, it should at least be departed from as little as possible.

The fall of caloric produces more motive power at inferior than at superior temperatures. Thus a given quantity of heat will develop more motive power in passing from a body kept at 1 degree to another maintained at zero, than if these two bodies were at the temperature of 101° and 100°.

When a gas varies in volume without change of temperature, the quantities of heat absorbed or liberated by this gas are in arithmetical progression, if the increments or decrements of volume are found to be in geometrical progression.

The difference between specific heat under constant pressure and specific heat under constant volume is the same for all gases.

Sadi Carnot was born in 1796. His brother, Hyppolyte, wrote that he was of delicate constitution, but that he managed to increase his strength "by means of varied and judicious bodily exercises." This note appears in an extract from Carnot's unpublished writings: "Vary the mental and bodily exercises with dancing, horsemanship, swimming, fencing with sword and with sabre, shooting with gun and pistol, skating, the sling, stilts, tennis, bowls; hop on one foot, cross the arms, jump high and far, turn on one foot propped against the wall, exercise in shirt in the evening to get up a perspiration before going to bed; turning, joinery, gardening, reading while walking, declamation, singing, violin, versification, musical composition; eight hours of sleep; a walk on awakening, before and after eating; great sobriety; eat slowly, little, and often; avoid idleness and useless meditation." On one occasion, Hyppolyte wrote, Carnot was out walking when a horseman "who was evidently intoxicated, passed along the street on the gallop, brandishing his sabre and striking down the passers-by. Sadi darted forward, cleverly avoided the weapon of the soldier, seized him by the leg, threw him to the earth and laid him in the gutter, then continued on his way to escape from the cheers of the crowd, amazed at this daring deed." Not long thereafter Sadi Carnot died of cholera following an attack of scarlet fever, at the age of thirty-six.