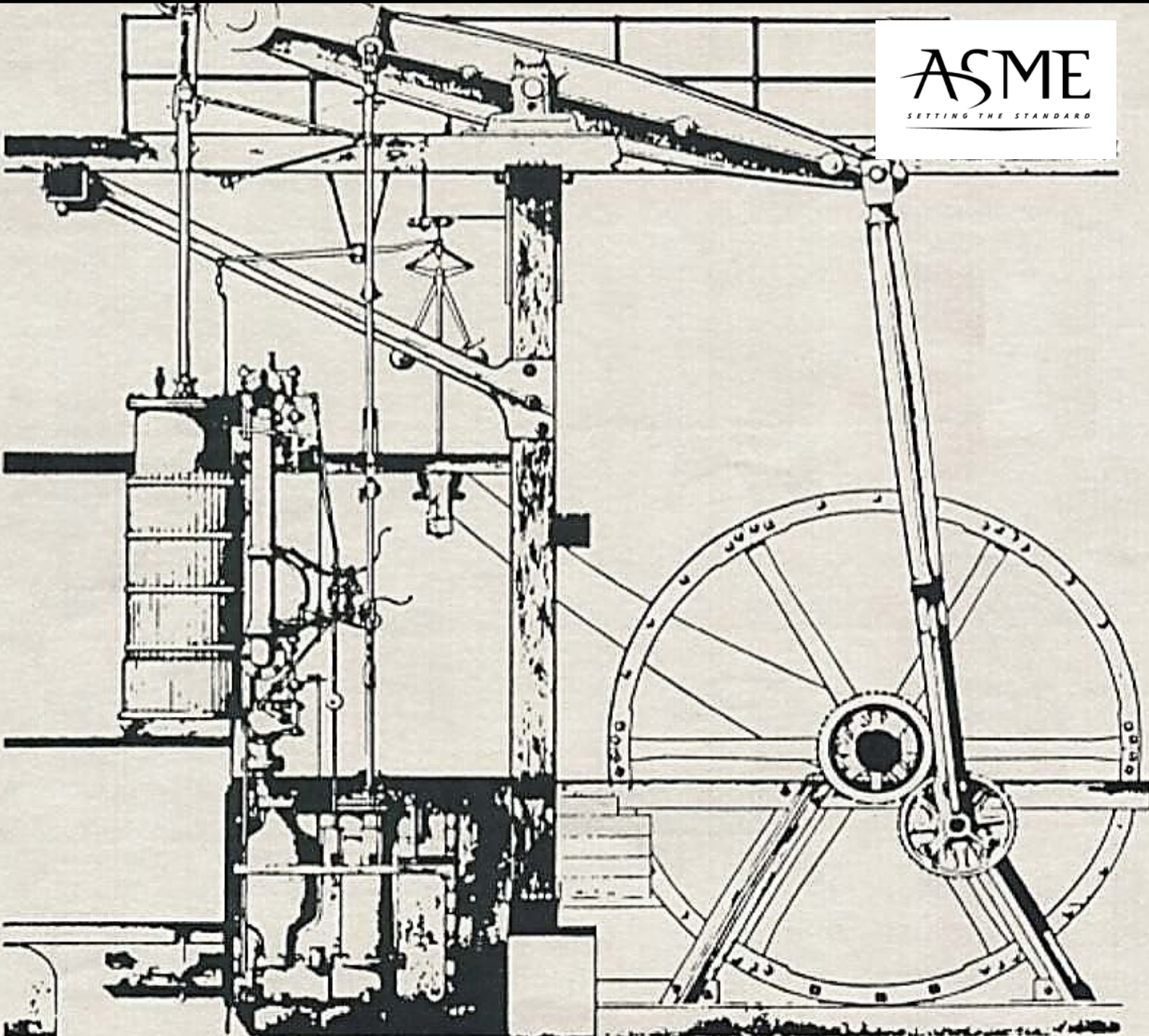


REFLECTIONS ON THE MOTIVE POWER OF FIRE AND ON MACHINES FITTED TO DEVELOP THAT POWER

By: **Nicholas Léonard Sadi Carnot** (1796 – 1832)

Publication Year: 1824

Designated a
HISTORIC MECHANICAL ENGINEERING LANDMARK by
THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS



Cover Illustration: The oldest surviving operable rotative steam engine. This engine by Boulton and Watt was built in 1785 for the London Brewery of Samuel Whitbread to drive its malt crushing mill. The engine incorporated many of the mechanical innovations that became steam engine practice, including a separate condenser, parallel motion, and centrifugal governor. This engine, now on display and in operable condition at the Powerhouse Museum in Sydney, Australia, was designated a landmark by ASME in 1986.

Landmark Designated by ASME in Spring 2021



ASME
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New York, NY 10016-5990

FOUNDATION OF A NEW ENGINEERING SCIENCE

Reflections on the Motive Power of Fire and on Machines Fitted to Develop that Power, a book published in 1824 in France, was among the earliest significant attempts to understand and explain the theory of heat engines—machines that convert heat into useful work.

The book's author, Nicholas Léonard Sadi Carnot (1796–1832), a French engineer and physicist, published this book when he was only 28 years old. Two of the critical questions he sought to answer were whether using a substance besides steam might improve the performance of heat engines and whether heat engines could be 100 percent efficient, that is, convert *all* of the heat they receive into useful work.

Carnot concluded that theoretically the working substance did not matter (but that for practical reasons some might be better than others) because the efficiency of a heat engine depended on the *temperatures* between which it works, not on the working substance. Higher efficiency is achieved when there is a greater *difference* between the temperature at which heat is supplied *to* a heat engine and the temperature at which heat is rejected or discharged *from* that engine.

Carnot's theoretical conclusions had practical repercussions. He noted:

"It is easy to see the advantages possessed by high steam pressure machines over those of lower pressure. The steam produced under a higher pressure is found at a higher temperature."

Initially, Carnot's work had little impact. The British physicist Eric Mendoza (1919-2007), in an introduction to a 1960 reprint of Carnot's book, concluded, "*There is little doubt that Carnot intended Reflections to be a popular book, not a*

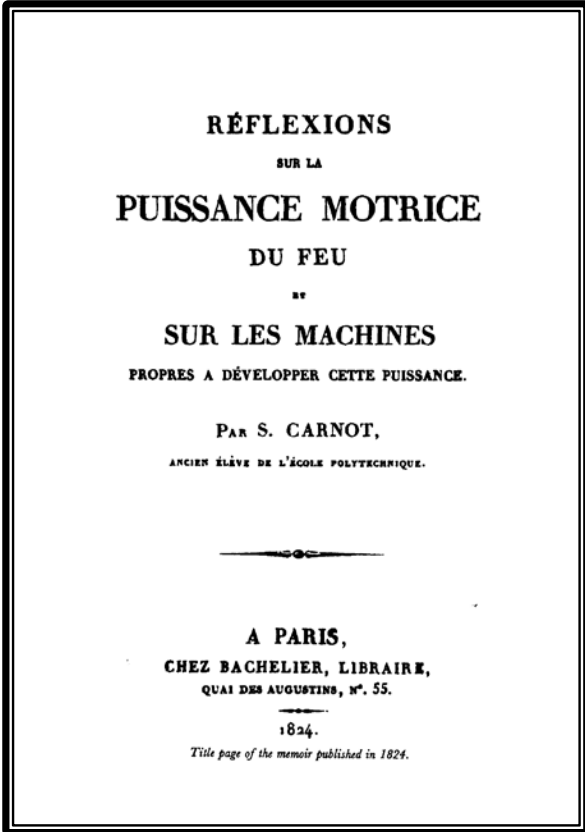
technical treatise. The text contains no arguments which depend on a calculus treatment—those are confined to the footnotes—but mostly verbal statement couched in simple but exact language. But apparently hardly anyone bought the book; a few years later booksellers had never even heard of it."

Yet *Reflections* eventually had a profound influence on the field by introducing a number of principles that became known as the Carnot cycle, the Carnot heat engine, Carnot's theorem, and thermal or thermodynamic efficiency.

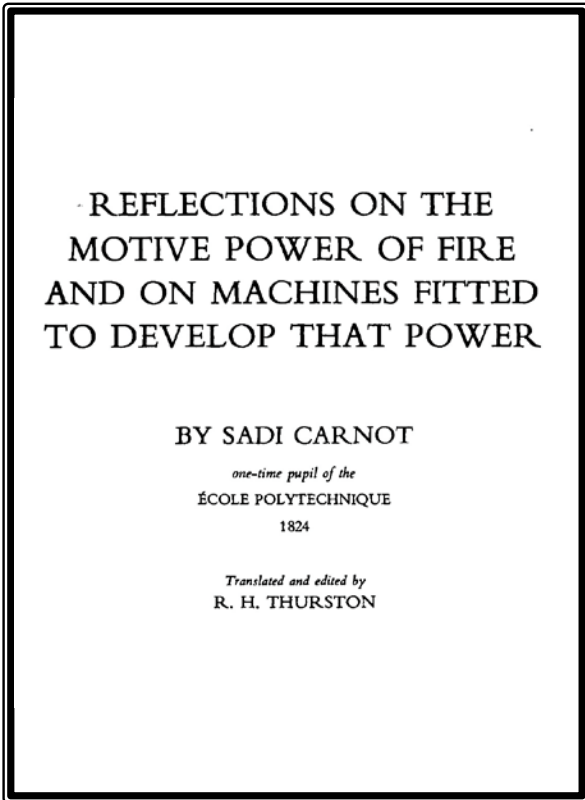
As author of the earliest major theoretical analysis of heat engines, Carnot is often considered the "father" of the new science of thermodynamics, a science developed by engineers applying scientific methods to man-made devices. Over the years, mechanical engineers exploited the thermodynamic principles developed by Carnot to advance the efficiency of heat engines (e.g. in power plants, automobile engines, jet engines, et.al.) by utilizing greater and greater temperature differences.

ASME recognizes that Carnot's work was extraordinary, especially for the time in which he lived. **For the legacy of knowledge that he has provided to the world, ASME is designating Carnot's book as a Historic Mechanical Engineering Landmark.**

A facsimile of the title page of Carnot's book in the original French and the title page of the translation into English are shown on the following page. Carnot's brief biography is included at the end of this brochure.



Left: Title Page of Carnot's Book (Image courtesy of Dover Publications, Inc.)



Left: English Translation of Title Page of Carnot's Book

From 1880 English Translation by Robert H. Thurston, First President of ASME (Image courtesy of Dover Publications, Inc.)

CONVERTING HEAT INTO MOTIVE POWER

The thermal machines that existed in Carnot's time were simple steam engines in which heat was supplied to a boiler by burning coal or wood, converting water in the boiler into steam, which in turn powered the steam engine. These engines had an efficiency of about two percent, meaning that only two percent of the heat energy in the fuel was converted to useful work; the remaining 98 percent was lost in the process. Most of that lost energy was in the form of heat contained in steam exhausted from the engine or in the heat contained in the flue gases going up the chimney.

Carnot recognized that, while contemporary steam engines converted heat into motive power, they were far from what an ideal machine could do, and he deduced the cycle (called the Carnot cycle) that an ideal heat engine—one with 100 percent efficiency—would have to follow.

Carnot knew, however, that even drastically improved heat engines could not—for a host of practical reasons—convert *all* of the heat energy supplied from coal or wood into motive power. Some of the heat would always escape or be discharged by the engine, making the process of energy conversion less than 100 percent efficient. His key insight, achieved through scientific reasoning, was that the efficiency of this conversion process depended not so much on the substance used (steam, air, or other material) but primarily on the *temperature* at which heat was supplied to the engine and the *temperature* at which heat was discarded. That finding, along with other conclusions he deduced, such as the ideal thermal cycle, led to the engineering science we today call thermodynamics. That science explains the relationship between heat and other forms of energy (e.g. mechanical energy, potential energy, and electrical energy).

In the almost two centuries since Carnot's publication, mechanical engineers have exploited

his principal of utilizing higher and higher *temperature differences*, advancing the technology and efficiency of heat engines by, for example, superheating steam or heating air to a high temperature before sending it to a machine and lowering the temperature at which the steam or air exits the machine. Such advances required the development of new materials that would have sufficient strength at high temperature and still be economical to use.

By the mid-20th Century, *typical* automobile engines achieved a thermal efficiency of 25-30 percent, diesel engines 35 percent, and steam-electric power plants 40 percent. Beginning in the late 20th Century, further increases in thermal efficiency in electric power production enabled some installations to approach 60 percent thermal efficiency with units that utilize both combustion (gas) turbines **and** steam turbines in a combined cycle. Although Carnot could not have envisioned the specifics of such combined cycle machines, he had a keen insight into their possibility when, in 1824, he speculated that:

“One of the gravest inconveniences of steam is that it cannot be used at high temperatures without necessitating the use of vessels of extraordinary strength. It is not so with air for which there exists no necessary relation between the elastic force and the temperature. Air, then, would seem more suitable than steam to realize the motive power of falls of caloric from high temperatures; perhaps at low temperatures steam may be more convenient. We might conceive even the possibility of making the same heat act successively upon air and vapor of water. It would be only necessary that the air should have, after its use, an elevated temperature, and instead of throwing it out immediately into the atmosphere, to make it envelop a steam boiler, as if it issued directly from a furnace.”

THE LAWS OF THERMODYNAMICS

Carnot based his theoretical reasoning on the analogy between the flow of water and the flow of heat. In a water wheel work is produced by water flowing from a higher elevation to a lower one. Similarly, in a heat engine work is produced by heat flowing from a body with a higher temperature to one with a lower temperature. While Carnot's analogy led to new insights into the operation of heat engines, it was not perfect. He assumed that heat (like water flowing over a water wheel) was conserved in the process. The concept that some heat was transformed into work had not yet emerged.

Carnot's recognition that perpetual motion (a device or machine that can do work indefinitely without an outside energy source) is impossible to achieve was an important step in the development of what eventually became known as the first law of thermodynamics, which states, in simple terms, that energy can neither be created nor destroyed but it can be converted from one form to another.

As the field of thermodynamics evolved after Carnot's death, additional laws were formulated, known as the 0th, 2nd and 3rd laws of thermodynamics, and the concept of entropy was established. Those subjects are beyond the scope of this brochure. Information about them may be found under "Further Readings."



Left: Sadi Carnot 1830 at age 34
(Image courtesy of Dover
Publications, Inc.)

ENERGY CONVERSION

Mechanical Engineering deals with, among other things, developing the means to **convert** one form of energy into another form of energy. Some examples are:

- Burning gasoline or diesel fuel (a chemical reaction that produces **heat energy**, also called thermal energy) in an internal combustion engine, converting that **heat energy** to **mechanical energy**¹ to:
 - propel a car, truck, or ship etc.
 - drive a pump or compressor or any other type of machinery
 - drive a generator to convert the **mechanical energy** to **electrical energy**
- Burning natural gas, coal or oil in a furnace (a chemical reaction that produces **heat energy**) to generate steam in a boiler (also called a steam generator) and then converting the **heat energy** in the steam to **mechanical energy** in a steam turbine or steam engine to:
 - propel a ship
 - propel a train
 - drive a generator to convert the **mechanical energy** to **electrical energy**
- **Fissioning** certain elements (a nuclear process that produces **heat energy**) to generate steam and then converting the **heat energy** in the steam to **mechanical energy** in a steam turbine to propel a ship or to drive an electric generator which converts the **mechanical energy** to **electrical energy**.
 - Burning natural gas or fuel oil (a chemical reaction that produces **heat energy**) in a gas turbine, converting that **heat energy** to **mechanical energy** to:
 - drive a generator to convert the **mechanical energy** to **electrical energy**
 - propel an airplane (a jet engine)
- Converting the **kinetic energy** of *falling* water to **mechanical energy** in a hydraulic turbine to drive an electric generator to convert the **mechanical energy** to **electrical energy**.
- Converting the **kinetic energy** of *flowing* water to **mechanical energy** in a water wheel to drive a mill or other machinery.
- Converting the **kinetic energy** of *blowing wind* to **electrical energy** in a wind turbine-generator.
- Converting **solar energy** into **electrical energy** in photovoltaic solar cells.

There are other examples of energy conversion, but the ones cited above are the basic ones that mechanical engineers have studied, exploited, and developed over the years. Steam power began to become important towards the end of the eighteenth century, shortly before Carnot published his book.

¹ What Carnot called “Motive Power” in the title of his book is often referred to today as “mechanical energy” or “mechanical work”. The term “motive power” is no longer commonly used except in the railroad industry.

HEAT AND TEMPERATURE WHAT'S THE DIFFERENCE?

Heat energy,² also called thermal energy, is often confused with temperature and vice versa. Carnot understood and explained the difference. Carnot also explained the conversion of heat energy into mechanical energy and the limitations of that conversion process.

HEAT

In engineering terms *energy* is defined as the ability to do mechanical work. Heat is one form of energy. In simple terms, mechanical work is the exertion of a force over a distance. Examples of work are pushing a boulder along the ground or raising a weight to a given height. The “weight” can be a solid or a liquid or a gas. It requires work for a person to climb a flight of stairs or for a crane to lift a steel girder to the top of a building. It requires work for a water pump to raise water. It requires work for a compressor to compress (increase the pressure of) a gas to push it through a pipeline.

Energy is required to do work. Energy exists in many forms and can generally be converted from one form into another. As explained on the previous page, mechanical engineering deals with, among other things, developing the means to **convert** one form of energy into another form of energy.

TEMPERATURE

Temperature is a *property (an observable characteristic that is measurable) of a material.* For example, temperature is a property of a substance that can be measured by a thermometer. Thermometers exist in many different forms, from the common bulb or dial thermometer used to measure the outdoor temperature to highly technical devices used to measure the temperature of molten steel or the exhaust temperature of a rocket engine.

Carnot reasoned that heat energy exists *only* when two or more substances are at *different* temperatures. If both materials are at the *same* temperature, heat energy between them does *not* exist. Further, heat energy always flows from the material at a higher temperature to the material at a lower temperature unless there is an outside influence. An example of an outside influence is a refrigerator or heat pump which moves heat energy from a lower temperature to a higher temperature. But a refrigerator or heat pump requires energy from an outside source to accomplish that.

2. Natural philosophers in Classical Greece believed that all of nature was composed of four elements: earth, water, air, and fire. Fire was believed to be the lightest of the four. By the late 18th century this ancient concept had yielded to new scientific theories regarding chemical elements, matter, and energy. Carnot understood that heat or “caloric” was a form of energy, but he must have liked the quaint and charming word “Fire” (Feu in French), since he used “Fire” instead of “Heat” or “Caloric” in the title of his book. Carnot and his contemporaries used the term “caloric” for what we today call heat.

HISTORIC MECHANICAL ENGINEERING LANDMARK

***REFLECTIONS ON THE MOTIVE POWER OF FIRE
AND ON MACHINES FITTED TO DEVELOP THAT POWER***
1824

THIS BOOK, PUBLISHED BY NICOLAS LÉONARD SADI CARNOT, PROVIDED THE FIRST GENERAL THEORY OF HEAT ENGINES AND EXPLAINED WHY, SINCE WATER UNDER HIGHER PRESSURE BOILS AT A HIGHER TEMPERATURE, STEAM ENGINES USING HIGHER PRESSURE STEAM ARE MORE EFFICIENT THAN ENGINES USING LOWER PRESSURE STEAM. *REFLECTIONS* LAID THE FOUNDATIONS FOR AN ENTIRELY NEW MECHANICAL ENGINEERING DISCIPLINE — THERMODYNAMICS. CARNOT'S WORK ATTRACTED LITTLE ATTENTION DURING HIS LIFETIME, BUT IT WAS LATER BUILT ON BY OTHERS TO DEVELOP THE LAWS OF THERMODYNAMICS, WHICH PROVIDED ENGINEERS WITH CRITICAL TOOLS TO CREATE MORE EFFICIENT MACHINES TO CONVERT HEAT INTO POWER.



AMERICAN SOCIETY OF MECHANICAL ENGINEERS — 2020

Above: Landmark designation plaque

OTHERS INVOLVED IN THE DEVELOPMENT OF THERMODYNAMICS

Carnot was not alone in the development of thermodynamics. As in all great scientific and engineering accomplishments, it takes the work of many to advance the work of pioneers. For example, Carnot’s deductions were based largely on logic and reasoning rather than mathematics. The importance of his work became widely apparent only after Émile Clapeyron in 1834 translated Carnot’s theory into a mathematical format. Some of the other notable engineers and scientists of the 18th and 19th centuries who contributed to the development of thermodynamics are shown in the table below.

NAME	CONTRIBUTION
Joseph Black (1728-1799)	Concepts of latent heat and specific heat
Benjamin Thompson (1753-1814)	Experiments undermining caloric theory; early demonstration of conversion of mechanical energy to heat energy
Émile Clapeyron (1799-1864)	Converted Carnot’s ideas into an analytical graphic form making them more accessible and compelling
James Joule (1818-1889)	Experimental establishment of the mechanical equivalent of heat; interconversion of forms of energy
William Thompson (Lord Kelvin) (1824-1907)	Absolute temperature scale; early formulation of the second law of thermodynamics
Rudolf Clausius (1833-1888)	First clear joint statement of first and second laws of thermodynamics, introduced the term “entropy;” blended Carnot’s work with new theories of heat
William Rankine (1820-1872)	Established accurate relationships between temperature, pressure, and density of gases; more comprehensive theory of heat engines than predecessors
James Clerk Maxwell (1831-1879)	Developed the ‘Maxwell thermodynamic relations’—statements of equality among the second derivatives of the thermodynamic potentials with respect to different thermodynamic variables.

FOR FURTHER READING

- M. Barnett, “Sadi Carnot and the Second Law of Thermodynamics,” *Osiris*, 13 (1958): 327-257.
- D. S. L. Cardwell, *From Watt to Clausius: The Rise of Thermodynamic in the Early Industrial Age* (Ithaca, N.Y.: Cornell University Press, 1971).
- D. S. L. Cardwell, “Power Technology and the Advance of Science 1700-1825,” *Technology and Culture*, 4 (1965): 188-207.
- W. H. Cropper, “Carnot’s Function: Origins of the Thermodynamic Concept of Temperature,” *American Journal of Physics*, 55:2 (1987): 120-129.
- S. S. Wilson, “Sadi Carnot,” *Scientific American*, 245:2 (Aug. 1981): 102-114
- Carnot’s *Reflections*, including selections from Carnot’s posthumous manuscripts, plus Émile Clapeyron’s *Memoir on the Motive Power of Heat* and Rudolf Clausius’ *On the Motive Power of Heat and on the Laws which can be Deduced from it for the Theory of Heat* – all in English – are available in a single paperback from Dover Publications (www.doverpublications.com).

NICOLAS LÉONARD SADI CARNOT

Adopted from the biography of Carnot by Mark Crawford (posted on ASME.org)

Nicolas Léonard Sadi Carnot, the son of high-ranking military leader Lazare Nicholas Marguerite Carnot, was born in Paris in 1796. His father resigned from the army in 1807 to educate Nicolas and his brother Hippolyte—both received a broad, home-based education that included science, art, language and music.

In 1812, the 16-year-old Nicolas Carnot was admitted to the highly esteemed *École Polytechnique* in Paris. His instructors included Joseph Louis Gay-Lussac, Siméon Denis Poisson and André-Marie Ampère; fellow students included famous future scientists Claude-Louis Navier, and Gaspard-Gustave Coriolis. During his time in school, Carnot developed a special interest in the theory of gases and solving industrial engineering problems.

After graduation, Carnot entered the French Army as a military engineer and served until 1814. In 1821, he visited his father, who had moved to Magdeburg, Germany. Lazare (his father) had seen a steam engine that had come to the city and father and son spent much of their time together discussing theories about how steam engines worked.

Carnot returned to Paris, excited to develop scientific theories about steam engines and heat; no researchers had yet discovered the fundamental scientific principles behind their operation. Most scientists believed in caloric theory, which maintained heat was an invisible liquid that flowed when it was out of balance. Carnot wanted to use his research to improve the efficiency of steam engines, which was only a meager two or three percent at the time.

Carnot had two key questions about heat engines he wanted to answer: Was the work available from a heat source unlimited? And can the efficiency of heat engines be improved by replacing steam with a different fluid or gas?

In 1824, Carnot published *Reflections on the Motive Power of Fire*, which detailed his research and presented a well-reasoned theoretical

treatment for the perfect (but unattainable) heat engine, now known as the Carnot cycle. In the first stage of his model, the piston moves downward while the engine absorbs heat from a source and gas begins to expand. In the second stage, as the piston continues to move downward, the heat is removed; the gas still expands but this time through a temperature drop. In the third stage, the piston starts to rise and the gas is compressed again, driving off heat (isothermal compression). In the fourth stage, the piston continues to move upward, the cooled gas is compressed and the temperature rises.

Carnot realized that the conduction of heat between parts of the engine at different temperatures had to be eliminated to maximize efficiency. He also introduced the concept of reversibility, whereby motive power can be used to produce the temperature difference in the engine. Also some of the theories he determined laid the groundwork for the discovery of the second law of thermodynamics.

Carnot died during a cholera epidemic that swept Paris in 1832, at the age of 36. Fearing they were contaminated, many of his writings were buried with him at his funeral—very little was saved. Unfortunately he did not live to see his work revered by other scientists. His ideas were incorporated into the thermodynamic theories proposed by Rudolf Clausius and William Thomson in the early 1850s. Rudolf Diesel also drew on Carnot's theories when he designed the diesel engine in 1893.

With his multiple scientific contributions, including the Carnot cycle, Carnot theorem and Carnot efficiency, Nicolas Léonard Sadi Carnot is often described as the "Father of Thermodynamics." His concept of the idealized heat engine led to the development of a thermodynamic system that could be quantified, a key success that enabled many of the future discoveries that lay ahead.

THE HISTORY AND HERITAGE PROGRAM OF ASME

Since the invention of the wheel, mechanical innovation has critically influenced the development of civilization and industry as well as public welfare, safety and comfort. Through its History and Heritage program, the American Society of Mechanical Engineers (ASME) encourages public understanding of mechanical engineering, fosters the preservation of this heritage and helps engineers become more involved in all aspects of history.

In 1971 ASME formed a History and Heritage Committee composed of mechanical engineers and historians of technology. This Committee is charged with examining, recording and acknowledging mechanical engineering achievements of particular significance. For further information, please visit <http://www.asme.org>

LANDMARK DESIGNATIONS

There are many aspects of ASME's History and Heritage activities, one of which is the landmarks program. Since the History and Heritage Program began, 275 artifacts have been designated throughout the world as historic mechanical engineering landmarks, heritage collections or heritage sites. Each represents a progressive step in the evolution of mechanical engineering and its significance to society in general.

The Landmark Program illuminates our technological heritage and encourages the preservation of historically important works. It provides an annotated roster for engineers, students, educators, historians and travelers. It also provides reminders of where we have been and where we are going along the divergent paths of discovery.

ASME helps the global engineering community develop solutions to real world challenges. ASME, founded in 1880, is a not-for-profit professional organization that enables collaboration, knowledge sharing and skill development across all engineering disciplines, while promoting the vital role of the engineer in society. ASME codes and standards, publications, conferences, continuing education and professional development programs provide a foundation for advancing technical knowledge and a safer world.

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The nomination of Carnot's book to be designated a Historic Mechanical Engineering Landmark, as well as this commemorative brochure, was prepared by Dick Pawliger, P.E. (Ret.). Dick, a Life Fellow of ASME, has been a member of its History and Heritage Committee since 2004 and served as its Chair from 2009 to 2015. He spent his 40-year engineering career with American Electric Power Co., helping to engineer, develop, construct, and operate large thermal power plants with progressively increasing thermal efficiency.