



Vaclav Smil

# Prime Movers of Globalization

**The History and Impact  
of Diesel Engines and Gas Turbines**



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## **Prime Movers of Globalization**

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# **Two Prime Movers of Globalization**

The History and Impact of Diesel Engines and Gas Turbines

Vaclav Smil

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## **Prime Movers of Globalization**



# 1

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## Globalization Waves and Their Prime Movers

. . . the new regime of the seas provoked a growing primacy of the Far West over other civilizations of the earth. . . . The circulation of ideas . . . took on a new pattern and velocity.

—William H. McNeill, *The Global Condition*

The phenomenon of globalization—the planet-spanning process of economic exchanges and information links, of complex flows of social and political influences, and of unprecedented environmental consequences—has been examined from many perspectives, with results ranging from highly arguable claims to insightful observations. The search for historical precedents has led to indefensible claims (such as Jack Weatherford’s 2004 conclusion that Genghis Khan was a thoroughly modern man who was committed to global commerce) and to simplistic misreadings of complex historical, social, and economic realities (such as Thomas L. Friedman’s 2005 exaggerated claims of a flat world). Among the most valuable contributions have been the examinations of links between economic globalization and planetwide environmental impacts, above all the process of anthropogenic climate change that encompasses a complex realm of causes and feedbacks (Alley et al. 2007).

But one approach has been rather conspicuously missing from these examinations—a focus on those techniques that have made this remarkable process possible. How have we arrived at the point of moving among the continents billions of tons of fuels, ores, cement, fertilizers, and feed- and foodstuffs and an enormous variety of industrial goods comprising ever-changing myriads of specifications and amounting commonly to tens of thousands and in some cases (most notably cars) even millions of tons per particular product? How it has come about that we can fly from virtually any place that has an airport with a runway long enough (at least 2.5 to 3 km) to accommodate large Boeing and Airbus jetliners to any other

similarly equipped place anywhere on the planet often within just sixteen and mostly within twenty-four hours?

How have these realities affected the performance of modern economies, and how have they shaped the course of modern history? How have they changed the extraction and trade of basic natural commodities, and how have they influenced the location of manufacturing and exports of finished products? What have been the major benefits and (often counterintuitive and intractable) drawbacks of this planet-scale transformation? A fundamental way of answering these questions requires first looking at the prime movers—the machines that convert naturally available (primary) energies into the mechanical power that is used to energize fleets of ships and airplanes (and also trains, trucks, and barges) and to compress the liquids and gases that are transported by pipelines, then contrasting their performance with the capabilities of their less effective predecessors, and, finally, outlining the principal consequences of these developments.

This mode of inquiry is one segment of studying history's grand sweep as a continuous (but unevenly progressing) transition to new prime movers—their invention, introduction, perfection, diffusion, and eventual displacement by more efficient, more reliable, and more affordable alternatives (Smil 1994, 2005, 2006, 2008). The greatest reward of this approach is that it informs us about the most fundamental physical determinants of the globalization process, as the dominant prime movers clearly delimit the cost, volume, speed, and reliability of transfers and trips whose aggregate forms the web of economic and human interactions on the global scale.

Civilizations that relied primarily on muscles and a few simple mechanical devices of limited power capacities and inherently low conversion efficiencies (that is, all premodern societies—from the earliest kingdoms of the Middle East to the city states of Italian Renaissance and the contending powers of the early modern Europe) had a greatly circumscribed scope of possible action and a distinctly slower tempo of life than their successors, which command increasingly more efficient and more reliable high-capacity prime movers. In turn, by extending this inquiry into the multifaceted economic, social, political, and environmental impacts of these technical innovations, we can better understand their possible future development and the need and timeframes of their modifications or displacements.

## Creating One World

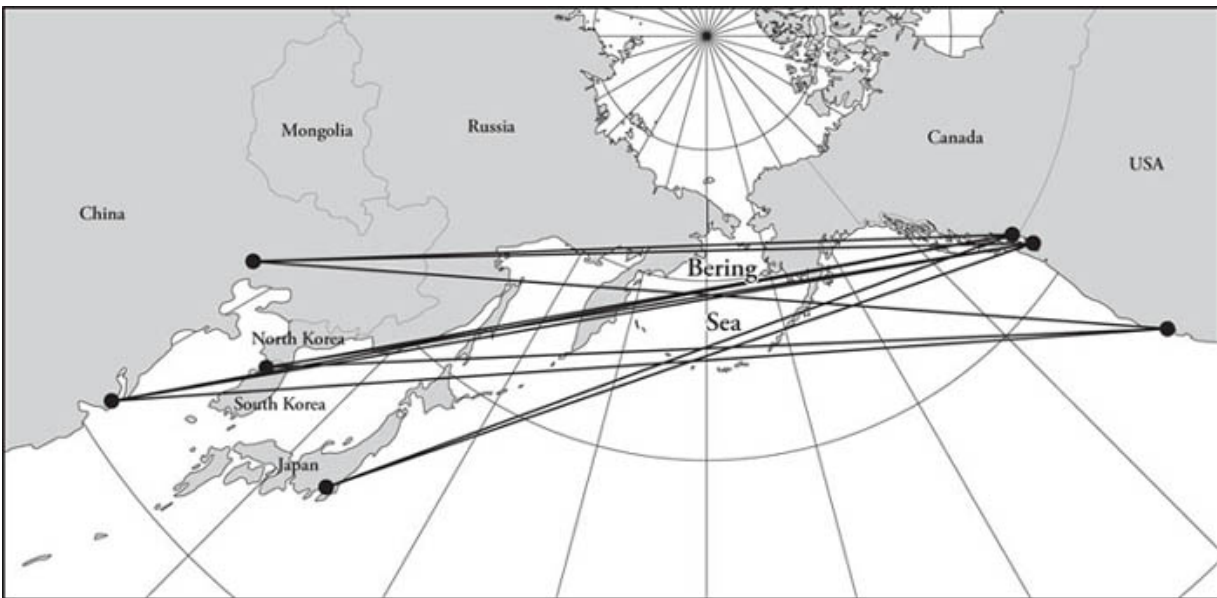
I have to make first a brief definitional detour. One of the most irritating attributes of the modern discourse of complex matters (whether they are political, economic, or environmental) is that many commonly used terms are left undefined, as if everybody were automatically on the same cognitive wavelength. As a result, we get such dubious designations as *sustainable development* (sustainable on what time scale?) or *American empire* (what is an empire?). The adjective *global* is, unfortunately, one of those undefined terms (Smil 2008). Its most logical primary use should be reserved to describe those natural processes that operate on a truly planetary scale and that subject every place on earth to its effects. The best examples are atmospheric circulation (a planetwide, climate-shaping process that is energized by solar radiation) and plate tectonics (the incessant grand reshaping of the earth's crust that is driven by the planet's internal heat).

But most of the time the adjective *global* is used not to describe true planet-spanning phenomena but merely to describe events and occurrences that are encountered on all continents (or in all oceans) or are experienced by all societies but that are not spatially continuous and hence do not have a truly global presence. Excessive soil erosion and problems with invasive species are excellent examples of this usage, as is the talk about a global increase in income inequality or a global challenge of effective health-care management. *Global economy* and *global trade* are terms that use the adjective's second meaning. No modern country can be economically autarkic, and improving quality of life has been predicated on intensifying trade in goods and services—but economic globalization surely does not have the all-encompassing reach of global atmospheric circulation or global plate tectonics.

At the same time, it is a fascinating reality (and one with far-reaching environmental consequences) that the globalization of trade and travel has been creating networks of such an extent and intensity that some regions of the world that had previously remained largely unaffected by human action and that are far away from any major concentrations of people and economic activity have been transformed into busy corridors—or into unexpected repositories of waste. By far the best example of the first transformation is the North Pacific, a vast region that had until recently experienced little human intervention. The region is now being overflowed

daily by hundreds of airplanes traveling between North America and Asia (fig. 1.1), and its waters are constantly crisscrossed by fleets of container vessels that bring Asia's manufactures to the world's largest import market. The North Pacific's Central Gyre, with its massive accumulation of plastic debris (Moore et al. 2001), exemplifies the second case.

And yet another qualification is needed—one that addresses the semantics of modern historical discourse. Although globalization has created a world system of connections, relations, and interdependencies, historians do not agree about the onset of this process and have been using some questionable terms to distinguish its stages. According to the standard Western (and hence Eurocentric) historical narrative, the creation of the world system began only some five hundred years ago, in 1492, which ushered in the great European voyages of long-distance discovery and the beginning of ceaseless capital accumulation after 1500 (Jones 1981; Hall 1985; Wallerstein 1974, 1979; among many others).



**Figure 1.1**

Jet engines changed the northernmost Pacific Ocean—which was previously one of the world's most isolated regions—into a major transportation corridor. Every day, many great-circle flights from North America to northeast Asia pass above the Bering Sea. Routes from San Francisco, Seattle, and Vancouver to Tokyo, Seoul, Beijing, and Shanghai are plotted on the gnomonic projection centered on the North Pole that shows great-circle routes as straight lines.

Andre Gunder Frank challenged this view by offering his “humanocentric alternative” and arguing that the contemporary world

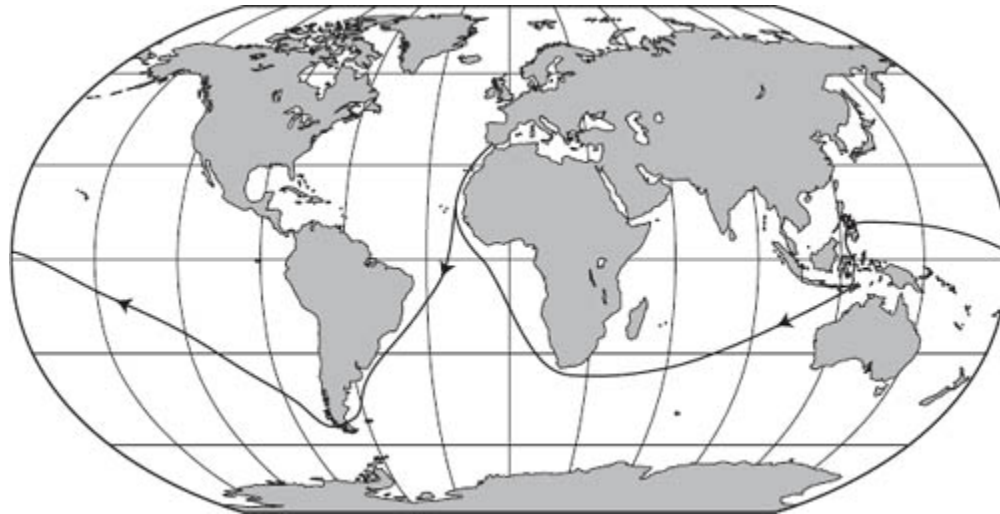
system has a history of at least five thousand years (Frank and Gills 1993). According to this definition, some kinds of globalization are as old as recorded history itself, and Cunliffe's (2008) examination of European prehistory shows that the existence of significant longdistance trade connections could extend that span even further. Although the archeological and historical evidence of well-organized and far-reaching interregional commercial exchanges is undeniable, such activities cannot be considered economic globalization.

Wallerstein used the confusing hyphenated term *world-systems* for interactions that do not have to be worldwide and that comprise the largest units of measurement still seen as coherent. The world of antiquity or the late Middle Ages thus had a number of world-systems. Similarly, Braudel (1985) differentiated between the unhyphenated *world economy* (an expression that he applied to the whole world) and the hyphenated *world-economy* (which for him encompasses only a fragment of the world and forms an economically autonomous section). In contrast, Frank used the unhyphenated *world system* for describing variously sized areas of interaction throughout what he calls Afroeuroasia that clearly did not take place on a global scale.

I have taken this semantic detour to make clear where I stand in my approach to globalization. Although the antique origins and subsequent transformations of considerable economic interactions across relatively large areas are historic truisms, the origins of planet-spanning networks go back only half a millennium. This era of relatively low-level globalization that began in the sixteenth century but whose impact became notable in the seventeenth and eighteenth centuries—Hopkins (2002) and Bayly (2004) label it *protoglobalization*, as opposed to the antique and medieval *archaic globalization* with its multiple regional centers—was followed by the first modern (and in many ways, quite limited) wave of nineteenth-century globalization that came to its end after World War I and whose relaunching was thwarted by the great economic crisis of the 1930s. Finally, the two prime movers whose history, diffusion, and impacts are examined in this book enabled the third (and astonishingly comprehensive and intensive) wave of global interaction and integration, and the great global recession that began in 2008 has made some commentators wonder if we are nearing its end.

The event that demonstrated the possibility of a truly global interaction of people and commercial activity was hardly a brilliant success. On September 20, 1519, Ferdinand Magellan (Fernão de Magalhães, a Portuguese captain in the Spanish service, where he was known as Hernando de Magallanes), left Spain in the command of five ships and 234 men to circumnavigate the world (fig. 1.2). In April 1521, he was killed on Cebu (in the Philippines). On September 6, 1522, Juan Sebastián Elcano, a Basque navigator, arrived in Spain after a journey of more than 20,000 km. The only surviving ship of that small fleet, the *Victoria*, carried just seventeen other men (and had spices loaded in the Moluccas in its hold) (Vial and Morente 2001). Carlos V gave Elcano a new coat of arms with a ribbon circling a globe inscribed *Primus circumdedisti me*, but the great captain had little time to enjoy his epoch-opening exploit: he died on another intercontinental voyage just four years later.





**Figure 1.2**

An 1810 engraving of Ferdinand Magellan (Fernão de Magalhães) and the route of the earth's first circumnavigation by the *Victoria* (1519–1522) (Magellan's portrait is available from the Library of Congress).

Within a century after this heroic (and tragic) proof of circumglobal navigation, there was a steadily increasing trade—in spices (light and pricey and hence suitable for long-distance exports) and cocoa, coffee and tea, fancy manufactures (porcelain and silk), unique raw materials (indigo and lac), and precious metals (silver and gold)—that connected Europe with the Americas, Africa, Asia, and Southeast Asia. The Honorable East India Company (it was incorporated on the last day of 1600) sent out its first ships in 1608 and set up its first Indian factory in Surat in 1615, and the Dutch *Verenigde Oostindische Compagnie* (also known as the United East India Company), established in 1602, chose Batavia as its Javan capital in 1619. The two enterprises became the two greatest enablers of this new web of commercial exchanges (Lestock 1971; Gaastra 2003; Cook 2007).

The global nature of these interactions is perhaps best demonstrated by a chain of trades centered on the era's most prosperous economy—the China of the late Ming and early Qing dynasties. A strong expansion of manufacturing and commerce in China generated a huge demand for silver that was further supported by a state tax that was payable in the metal. This demand was met primarily by large-scale mining of silver in Spanish America and its transfer, via Manila, to China. In turn, this transfer financed the flows of silk, porcelain, and other Chinese manufactures to Europe. A large-scale intercontinental system of trade created by China's unmatched



economic expansion thus tied Europe, the Americas, and Asia (Flynn and Giráldez 1995; Frank 1998).

On a personal level, these exchanges were manifested in Europe by an increasing accumulation of possessions made in different parts of the world. The homes of wealthy Dutch and English merchants were the first ones to display paintings, maps, globes, rugs, tea services, musical instruments, and upholstered furniture brought from distant countries (Mukherji 1983). These commercial activities intensified considerably during the eighteenth century as European discoveries came close to completing the map of the earth's oceans. Before the century's end, James Cook (1728–1779) became the first European to land on the eastern coast of Australia (1770), to stumble onto the Hawaii Islands (1778), and to map the Pacific Northwest coast all the way up to the Bering Strait (Low 1906; Thomas 2003) (fig. 1.3).

By the time that a new, post-Napoleonic order became established in Europe in 1814, all major islands and all great sailing passages (except for the seasonally frozen Arctic route from the northwestern Atlantic to the Bering Sea) were open for further exploration, commerce, and human interaction. By that time, the houses of affluent European families contained items from China, Japan, India, the Middle East, and parts of Africa and the Americas. Long-distance trade had also brought new consumption habits, and coffee, tea, and cocoa became widely sought after drinks. Although the overall volume of intercontinental trade remained small in absolute terms, its expansion proceeded fairly rapidly. Maddison (2007) estimated that between 1500 and 1820, world trade grew by nearly 1 percent per year (that is, doubling every seventy years), three times faster than the growth of global economy.

Sails were the prime movers of this pioneering wave of globalization that began at the beginning of the sixteenth century and lasted for just over three centuries. Sail is a fabric airfoil (a vertical wing) that converts wind's kinetic energy into the forward motion of a vessel as the air-pressure differences that act on it generate lift and drag forces (Marchaj 2000). The effect can be modeled by resorting either to Bernoulli's (incompressible flow) equation or to Euler's equations relating the velocity, pressure, and density of a moving fluid. Even when setting aside the difficulties and risks that are inherent in mounting, unfurling, and trimming those heavy expanses of canvas on tall-mast ships, this was a prime mover with notable

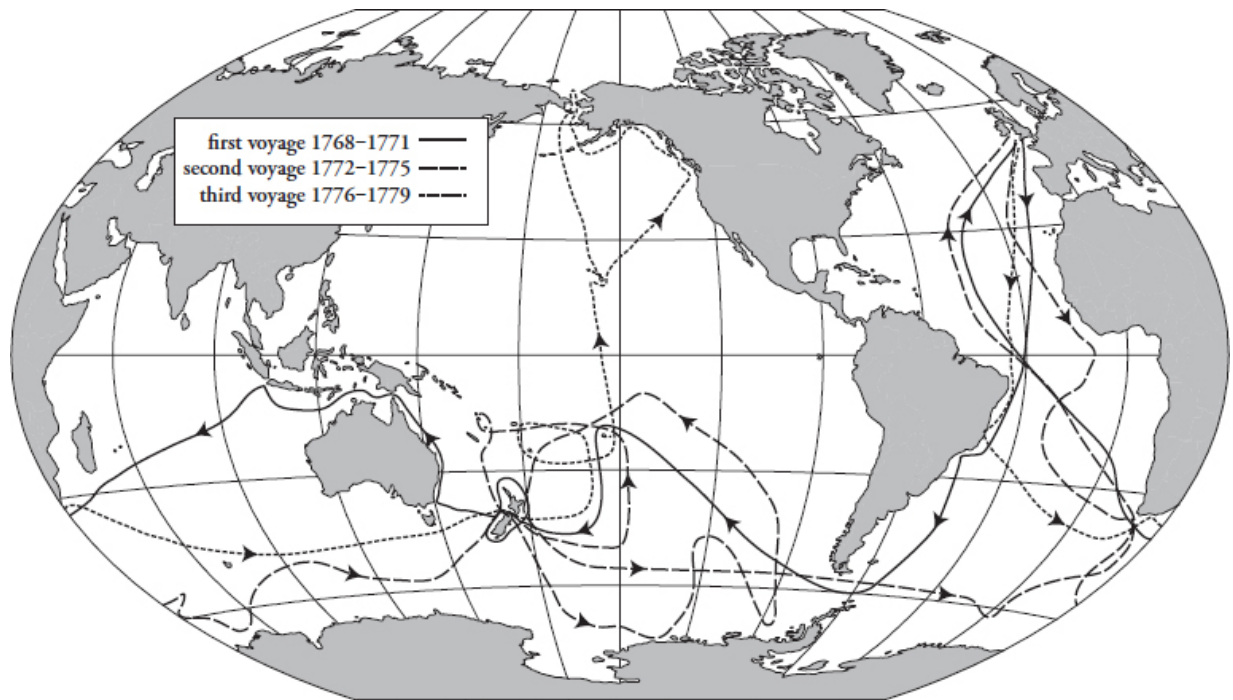


limitations. Winds astern created lift that far surpassed drag, and they propelled a ship forward. But with winds on the beam or slightly ahead of it, the force pushing a vessel sideways was greater than the one propelling it forward, and if a ship attempted to steer even closer to the wind, the resulting drag pushed it backward.

The square sails of antiquity that were set at right angles across the ship's long axis made it possible to sail forward only with the wind directly astern or less than 30 degrees off the course. Otherwise, they had to resort to wearing—changing course by making a complete downwind turn. Medieval square-rigged ships could sail with the wind on their beam (90 degrees), and by the sixteenth century they could travel at an angle of about 80 degrees into the wind. Only the combination of a larger number of loftier and more adjustable square and triangular sails made it possible to sail closer to the wind. Vessels with square sails and triangular mizzens could proceed with the wind at 62 degrees, and those with fore-and-aft rigs (triangular, lug, sprit, and gaff sails) could use winds close 45 degrees. For comparison, the aerodynamic limit that is realized in modern yachts is 30 degrees.



*CAPTAIN, JAMES COOK.*



**Figure 1.3**

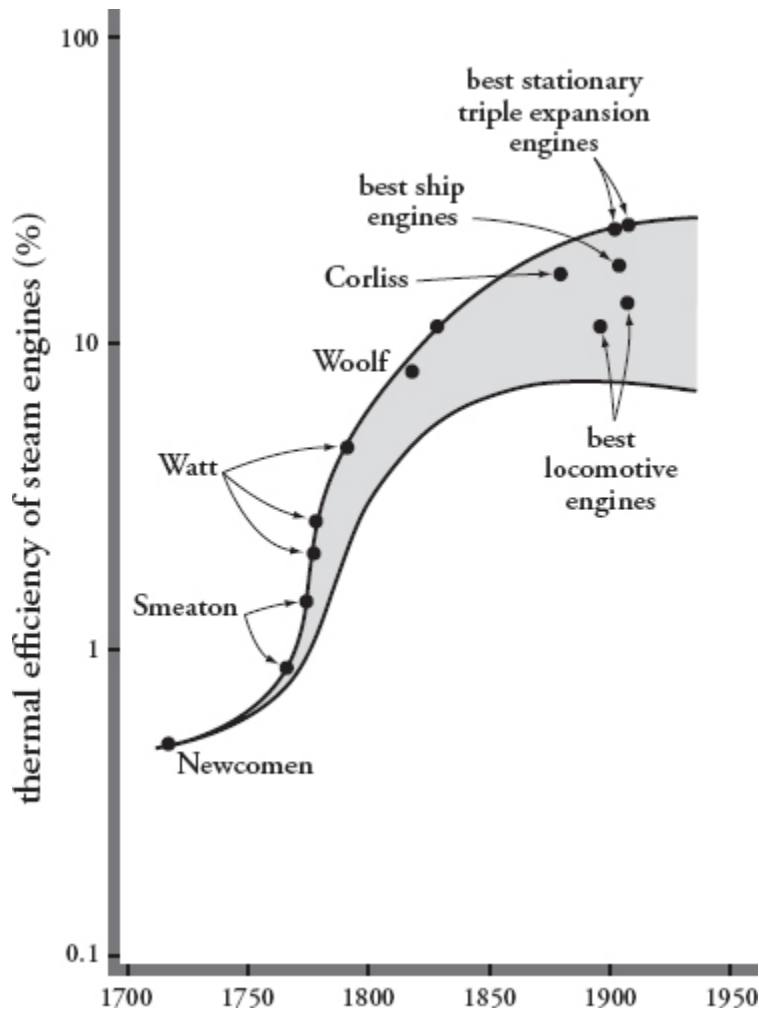
Captain James Cook (1728–1779), in an early nineteenth-century engraving by Nathaniel Dance, and his three great voyages (Cook’s portrait is available from the Library of Congress).

Wind and sails continued to propel many merchant ships during the first era of true commercial globalization, which took place in the two generations preceding World War I. Their most remarkable deployment was on the famous tea clippers, whose sailings between China and England and the United States set new speed records. In 1853, the *Lightning* sailed 803 km in a single day, at an average speed of 9.3 m/s and in 1890, the *Cutty Sark* traveled 6,000 km in thirteen consecutive days, at an average speed of 5.3 m/s (Armstrong 1969). For comparison, Roman cargo vessels in the Mediterranean did not travel faster than 2 to 2.5 m/s. But by the time that fast clippers sailed, the era of sailing ships was nearing its abrupt end, and they were displaced by the first fossil-fueled mechanical prime mover—the increasingly powerful, progressively more efficient, but always bulky, heavy, and (even at its best) very wasteful steam engine.

The earliest steam engines had a mass-to-power ratio as high as draft animals (that is, on the order of 1,000 g/W), and their poor efficiencies (Newcomen’s machines built in the second decade of the eighteenth century converted only about 0.5 percent of chemical energy in coal into reciprocating motion) limited their use to coal mines (Rolt 1963). Watt’s

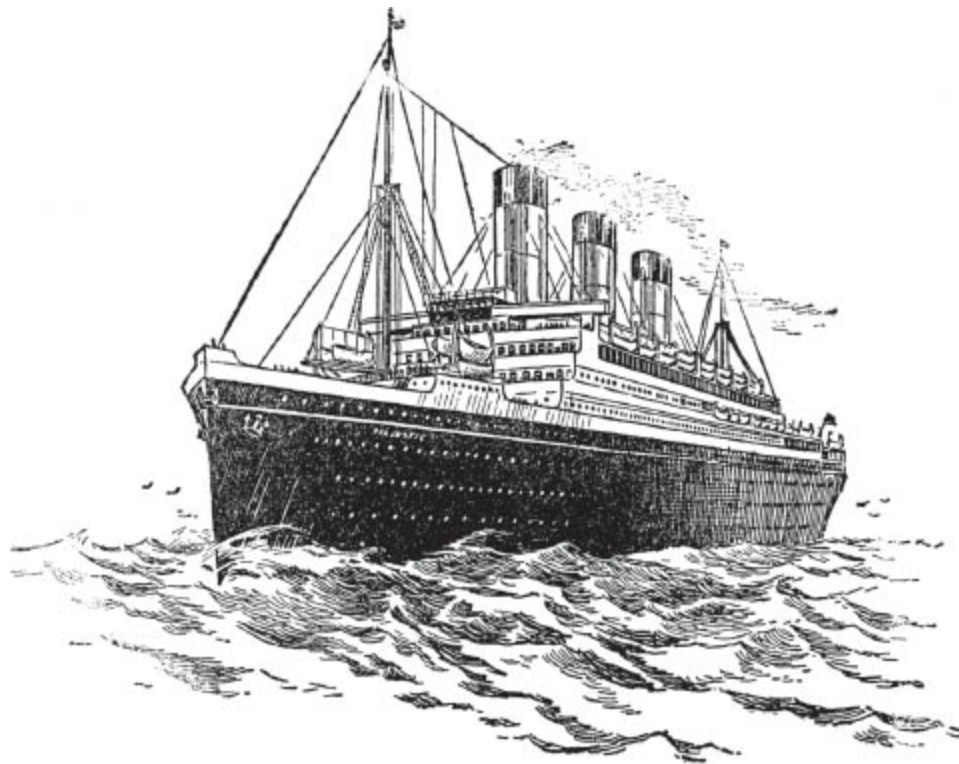
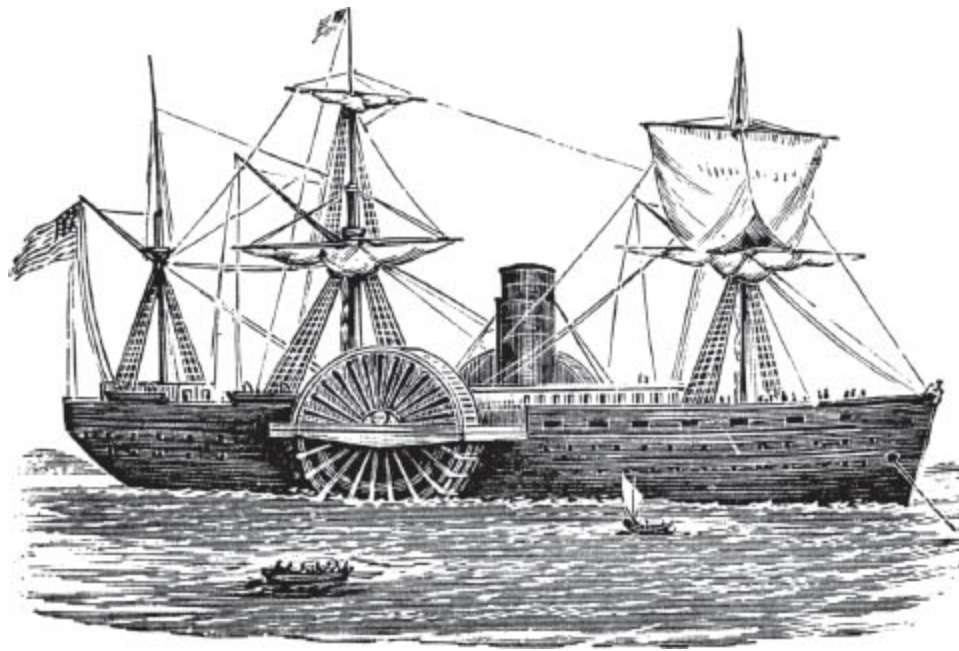
improvements (above all, the addition of a separate condenser, which was patented on January 5, 1769) raised the efficiency by nearly an order of magnitude to as much as 3 to 4 percent (fig. 1.4), and the highpressure engines that followed in the early nineteenth century after the expiration of Watt's patent made the machines light enough for use on railways and efficient enough to power ships that had to carry their own fuel on extended voyages (Smil 1994). Their first maritime applications came in the 1830s, when paddle-wheel-propelled ships crossed the Atlantic (Fry 1896). The first eastward run was in 1833, when the *Royal William* traveled from Quebec to London, and the first westward run was the race between the paddlewheels *Sirius* and *Great Western* in 1838. But even by 1850, the *Atlantic* was still fully rigged (fig. 1.5).

Two advances made steamships the dominant means of transport and by far the most important prime movers of the second, more concentrated, and more intensive wave of globalization that began before the middle of the nineteenth century and that was abruptly terminated by World War I. First, inefficient and inherently slow paddle wheels were replaced by screw propellers. The first practical ones were tried out by John Ericsson in the United States in 1838 and by Francis P. Smith in the United Kingdom in 1839 and installed on merchant vessels in 1840 (Burgh 1869; Jackson 1920). Second, the rising power and efficiency of steam engines enabled the construction of much more massive ships with metal hulls that could travel faster without increasing their demand for coal. Iron hulls came first in the 1840s, and after the inexpensive steel made in Bessemer converters (introduced in the late 1850s) became widely available, superior all-steel hulls followed in the 1860s. The combination of the best steam engines and steel hulls introduced the age of the giant Atlantic liners of the late nineteenth and the early twentieth centuries (fig. 1.5).



**Figure 1.4**  
The increasing efficiency of steam engines, 1710 to 1910 (from Smil 1994).

By the century's end, the largest steam engines were about thirty times more powerful than they were in 1800, their best efficiencies were roughly ten times higher, and their mass-to-power ratios were less than 200 g/W (see [fig. 1.4](#)). These engines powered fleets of freight and passenger ships that connected the five continents with regularly scheduled traffic—leisure travel, intercontinental migration, and relatively large-scale, long-distance exports of raw materials and finished goods. Transporting people made a greater difference during this era of globalization than transporting goods. Most of the 60 million emigrants who left Europe between 1815 and 1930 for overseas destinations, above all for North America (Baines 1991), traveled on steampowered ships.



**Figure 1.5**  
The fully-rigged, steam-engine-powered *Atlantic* of the Collins Line operated between 1850 and 1858. The *Bismarck* was launched in 1914. It was ceded to Great Britain in 1922 and sailed as the *Majestic* of the White Star Line until 1936.



Increasing labor productivity and strong economic growth (averaging globally over 2 percent per year in the two generations before 1914) in Europe and North America brought larger disposable incomes and led to major dietary changes. This rising demand for food (both staples and a greater variety of meat and fruits products) was best satisfied by specialized producers who had a comparative advantage thanks to mild climate or low labor costs. As a result, international trade in foodstuffs began to expand beyond the imports of low-volume luxury items (cocoa, tea, and spices) as soon as the long-distance transportation of bulky commodities (especially grains) and refrigerated meat (from North America, Australia, and Argentina) could be done by the relatively large-capacity steel-hull ships that became common during the 1880s. Yet another important driver of large-scale commercial globalization was the accelerated expansion and maturation of the British empire (Cain and Hopkins 2002).

Maddison's (2007) data indicate that world trade expanded at an average rate slightly exceeding 4 percent per year between 1820 and 1870 (which was more than four times faster than the growth of world economy) and continued at a strong rate of 3.4 percent per year until the beginning of World War I. Between 1870 and 1913, the share of exports in the total economic product in ten of the most industrialized countries rose by 50 percent (to about 12 percent), and by 1913, the percentage of countries' gross national product that originated from exports was 25 percent for the United Kingdom, Australia, and Canada and about 20 percent for Germany and Italy (Maddison 1995). This means that some countries were relatively nearly as dependent on exports in 1900 as they are now and that the rising volume of world trade began to narrow national price differentials for agricultural commodities, ores, and metals.

In 1906, the British satirical weekly *Punch* carried a full-page cartoon depicting a gladiatorial allegory of free trade defeating protectionism (fig. 1.6). This celebration was premature. More than a century later, nations continue to conduct seemingly endless rounds of talks that are designed to eliminate (or at least reduce) major trading barriers, and some of the world's richest economies persistently retain enormous subsidies for domestic farm products and offer generous tax breaks for resource exploitation or manufacturing. Moreover, there are no indications that these barriers to a truly free trade will end anytime soon, and the global recession of 2008 and 2009 (the deepest one since World War II) renewed concerns about perilous

protectionism. On the other hand, expanding international trade has always exacted various human, economic, and environmental costs (ranging from radical transformations of labor markets to uncontrolled air and water pollution) (I address this contentious topic of undesirable consequences in detail in [chapter 6](#)).



POLICY VERSO.

**Figure 1.6**  
A gladiatorial allegory of free trade triumphant. The caption is a pun on the Latin phrase *police verso* (“thumbs down”) (reproduced from *Punch*, January 24, 1906, p. 65).



Expanding steam-powered intercontinental trade meant that the poor energy-conversion efficiency of steam engines had to be overcome. The operation of those engines required nearly incessant stoking. As Suplee (1913, 306) noted, “there is probably no more laborious and exhausting work demanded of human beings than that required in the stokehold of a great steamship.” Stokers had to work in infernal conditions, and the loading and offloading done by the stevedores was also physically demanding. The expanding trade was carried by relatively small generalpurpose cargo (break bulk) ships that typically had capacities of no more than 5,000 to 6,000 dwts. These ships had to be laboriously loaded and offloaded by small armies of stevedores, who only sometimes were helped by low-capacity steam-powered cranes.

Steam-powered trade was also rather slow. Even the best steam engines allowed speeds of no more than about 15 kilometers per hour. Despite these drawbacks, the importance of these vessels declined only gradually during the first half of the twentieth century, and even during World War II, the single largest group of new cargo carriers were the Liberty-class (EC2) ships that were powered by three-cylinder steam engines (each supplied by two oil-fired boilers) that were rated at 1.86 MW (Bunker 1972; Elphick 2001). These vessels had capacities of 10,500 dwt and sustained speeds of nearly 20 km/h, and U.S. and Canadian shipyards built 2,710 of them to carry military materiel, food, and troops to Europe and Asia (fig. 1.7). After the war, the U.S. Navy sold most of them cheaply as surplus materiel, and they continued to carry commercial cargo into the 1960s.

The third wave of globalization—the post-1945 era of rising interdependence and integration that has made the extent and the intensity of today’s global economy possible—has been physically enabled by two different prime movers—(1) highcompression, nonsparking, internal-combustion engines, which were invented and developed to the point of first commercial applications by Rudolf Diesel (1858–1913) in the 1890s, and (2) gas turbines, whose first successful prototypes were designed by Frank Whittle (1907–1996) and Hans-Joachim Pabst von Ohain (1911–1998) in the 1930s. Understanding the history of these machines and the reasons for their success leads to more than just a better appreciation of the fundamental physical forces behind globalization.

A lengthy process of machine development, commercialization, and diffusion of diesel engines provides perfect examples of gradual technical

advances that have received little public attention, that may not be ranked among pivotal modern inventions even by informed professionals, but that have led to epochal shifts in world affairs by creating the indispensable driving forces of the global economy. This book is concerned with the evolution and impact of diesel engines, and readers who wish to explore their technical details should consult the very large volume (more than 1,000 pages) edited by Mollenhauer (2001). Similarly, readers seeking a deeper technical understanding of jet engines should turn to books by Hill and Peterson (1992) and Cumpsty (2003).



**Figure 1.7**

Liberty-class ships powered by oil-fired steam engines were America's principal WWII material carriers. This is a photograph of the refurbished S.S. *Jeremiah O'Brien* (available from the National Liberty Ships Memorial at <http://www.ssjeremiahobrien.org/jobtonormandylarge.jpg>).

The massive (mostly two-stroke) diesel engines that power every kind of oceangoing cargo vessels and the gas turbines that propel jet airplanes are fundamentally (that is, in energetic, physical sense) more important to the global economy than are any particular corporate modalities or international trade agreements. The latter can be (and often are) easily renegotiated or abrogated, and the former do not have (as yet) any equally capable substitutes. This conclusion implies no simplistic technodeterminism; it

merely states the obvious. The engines are neither the cause nor even a principal cause of globalization. The human quest for a higher standard of living, profits, and power and the human propensities for long-distance trade and exploration have been the key motivating forces. But without the two prime movers, trade would not have achieved its truly planetwide scope or have done so at such massive scales, at such rapid speed, and at such affordable costs.

The widespread commercial adoption of the two engines also illustrates the importance of gradual improvements in efficiency, reliability, high-level performance, and environmental impacts of these now ubiquitous prime movers. Before surveying the advances and accomplishments of the two epoch-making techniques, I should answer two questions. What makes these two internal-combustion engines qualitatively different from their pioneering predecessor—the Otto-cycle, four-stroke gasoline-fueled internal-combustion engine? And why could that engine—one of the most commonly produced complex machines of the twentieth century—not compete in providing the most important transportation functions (trucking, railroad traction, waterborne shipping, and long-distance flight) that are now powered by diesel engines and gas turbines?

# 2

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## Why Gasoline-Fueled Otto-Cycle Engines Would Not Do

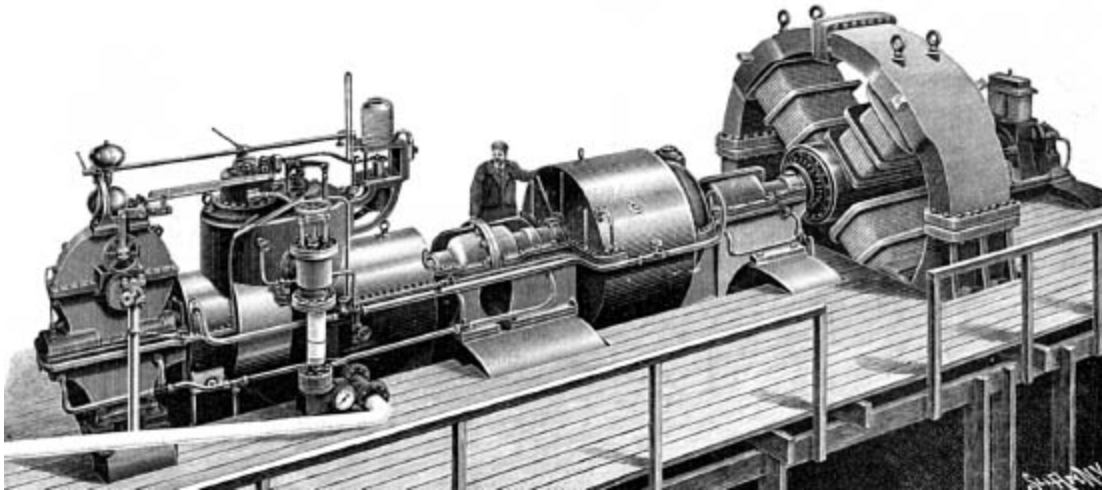
In gas-motor engines . . . an explosive mixture of combustible gas and air is introduced into the engine-cylinder, where it is ignited, resulting in a sudden development of heat and expansion of the gases, a great portion of the useful effect being lost by absorption of heat.

—Nicolaus A. Otto, U.S. Patent No. 194,047 filed July 13, 1876

No technical inventions arise entirely and instantly *de novo*. A closer look at the history of their development shows often long periods of theoretical gestation or preliminary exploratory experiments or an interaction of both. For decades, such processes may not result in any practical products, but they help to constrain the parameters of eventual viable designs. Eventually, this protracted evolution may bring an entirely new departure—a new class of machines, a new kind of material or compound, or a new process of extraction, conversion, or production. That was the case with the invention (and relatively rapid commercialization) of the first practical internal-combustion engines, which were fueled first by coal gas and, starting in the 1880s, by gasoline. A more common outcome brings inventions that belong to the same family of technical advances as does an original epoch-making design but whose attributes are so different (and in some respects, so superior) that they present unprecedented possibilities and open new horizons. That was the case with Diesel’s engine and with the gas turbine.

Using the standard nomenclature of biological systematics, both of these commonly used machines belong to the same kingdom (*regnum*) of artifacts. The kingdom of engines includes complex contrivances that are designed to convert the chemical energy of fuels into the mechanical energy of either reciprocating or rotary motion. The other important modern prime movers—hydraulic turbines and wind turbines—are not engines because their operation does not involve any transformation of matter. Engine classification can be based on the working cycle (two- or four-stroke),

ignition method (sparking or compression), basic mechanical design (reciprocating or rotary), cylinder arrangements, valve or port design and location (overhead, underhead, or rotary), fuel, fuel-mixture preparation (carbureting or fuel injection), cooling, engine applications (automotive, aero, or marine), and several other considerations (Taylor 1985; Heywood 1988).



**Figure 2.1**

The world's first 1-megawatt steam turbogenerator was installed in 1900 at the Elberfeld plant in Germany (from *Scientific American*, 1901).

Consequently, the hierarchy outlined below is just one of many classification possibilities as it attempts to proceed from the most fundamental features to less important differences. The kingdom of engines has two distinct phyla—one using external combustion and the other using internal combustion. Steam engines and steam turbines are the prime examples of the first kind; reciprocating steam engine is now only of historic interest, but steam turbines (which receive highly pressurized superheated steam from large boilers) are the world's most powerful continuously working machines and generate most of the world's electricity. At the beginning of the twentieth century, these rotary engines rated no more than 1 MW (fig. 2.1) and operated at pressures of just 1 MPa, with steam at less than 200°C and efficiencies of just around 5 percent. Today's largest units rate more than 1 GW, receive superheated, highly pressurized steam (more than 600°C and over 20 MPa) and convert just over 40 percent of fuel's chemical energy into electricity (Smil 2003).

All automotive and aeroengines and gas turbines rely on internal combustion. There are two major classes of internal-combustion engines. Hot combustion gases are used either to generate reciprocating motion of pistons in enclosed chambers (nearly all gasoline- and diesel-fueled engines) or to produce rotary motion in unique gasoline-fueled engines that were patented by Felix Wankel in 1957 (Hege 2001) and in all gas turbines. Continuing the taxonomic analogy, the reciprocating internal-combustion engines have two distinct orders of machines—those working with a closed cycle (the most common example is a submarine diesel engine that uses stored oxygen) and those that have an open cycle and discharge their working fluid after a single pass (all automotive and aero engines belong to this category).

Reciprocating engines have two main families—those that work without compression and those that confine their gases under compression. The earliest internal-combustion engines worked without compression and hence with very low efficiencies and with very large cylinders, while all modern engines operate under pressure. The two principal genera of reciprocating compression engines are non-sparking engines and those using an electric spark to ignite the fuel, and two distinct species use either a two-stroke or four-stroke working cycle. Completing the taxonomic analogy, at the subspecies and varietal levels, the internal-combustion engines could be distinguished by the arrangement of their cylinders (in-line, V, radial, opposite, and so on), by the fuel they use (various gases and liquids, with some engines capable using both interchangeably), and by the cooling method (air or liquid).

The diesel engines that power cars, trucks, and ships are thus internal-combustion machines with reciprocating motion and an open cycle, working under compression and without sparking in either a two- or four-stroke cycle that is fueled by medium-density refined liquid fuel. Three distinct features of gasoline-fueled (or ethanol-fueled) engines are their fuel ignition by electric sparking, their relatively low compression rate, and their need for the lightest refined liquid fuels. Gas turbines use open-cycle high-compression internal combustion to generate continuous rotary motion, and their most common fuels are natural gas (to generate electricity in stationary application or to power compressors or pumps) or kerosene (a refined fuel that is slightly heavier than gasoline) for aeroturbines (jet engines). In

chapter 4, I explain the differences between their two principal varieties—turbojets and turbofans.

A gas turbine is an internal-combustion engine in which fuel introduction, compression, ignition, combustion, and ejection of hot gases do not take place intermittently in sequenced stages (as they do in Otto-cycle or Diesel's engines) but occur concurrently and continuously in different parts of a machine. But even the most advanced gas turbine owes a great deal to the gasoline-fueled engine. Decades of perfecting those more-than-a-century-old machines have created advances in materials, casting, machining, assembly, electrical and electronic controls, and preventive maintenance that have been of immense help in designing and building the first prototypes and the first practical versions of gas turbines.

But why could the gasoline-fueled four-stroke engine not provide the same services at a comparable level of cost, comfort, and reliability? After all, it is both the most common prime mover of modern civilization and the one with the greatest aggregate installed capacity. There are now roughly 1 billion of these engines installed in cars, trucks, motorcycles, agricultural and garden machines, boats, snowmobiles, and airplanes, and the engines are also used in stationary applications, mainly in power pumps and as back-up and emergency electricity generators. Their aggregate global installed power is nearly twenty times as high as the total power of the largest stationary prime movers—the massive steam turbogenerators that are used in large thermal electricity-generating plants. To understand why this impressive machine has not become the prime mover of modern globalization in mass transport of goods or in long-distance flight, it is necessary first to appreciate the history of gasoline-fueled engines and then to contrast their performance and limits with those of the two competing prime movers.

### **The Early History of Internal-Combustion Machines**

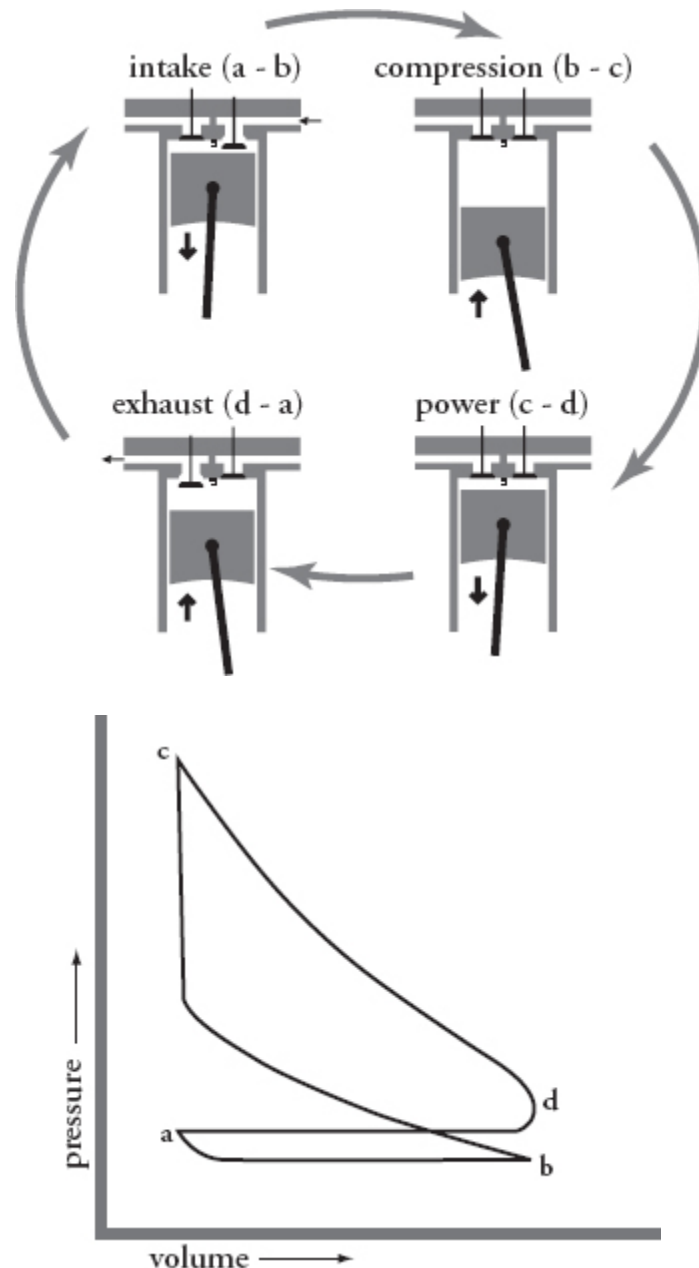
The idea of using hot gas rather than steam as a working medium had been around for nearly a century before the first commercial internal-combustion engines were built during the 1860s. The first conceptual designs go back to the closing decades of the eighteenth century and some serious attempts to build practical prototypes were made during the first half of the nineteenth century (Cummins 1989) The first commercially produced internal



combustion engine was patented in 1860 by Jean Joseph Étienne Lenoir (1822–1900), and it betrayed its steam-engine pedigree. It was a noncompressing, horizontal, double-acting machine with electric-spark ignition that ran at just 200 rpm and had an efficiency of less than 4 percent. Nearly five hundred units (rating about 2 kW) were made during the 1860s to power tasks that called for interruptible power, and although Lenoir made a single test (in 1862) of a liquid-fueled version of the engine to propel a three-wheel cart over 18 km, he did not pursue any further improvements after the 1860s.

The four-stroke engine, whose countless permutations came to dominate the vehicular uses and powered the first five decades of flight, had two remarkable and entirely independent origins—one a theoretical design that was never transformed into a working machine and the other a result of persistent incremental innovation by a dedicated innovator. The theoretician was a French engineer, Alphonse Eugène Beau (1815–1893, subsequently known as Beau de Rochas), who patented his idea on January 16, 1862 (Payen 1993). He described the principle of a four-stroke engine powered by a gas-air mixture that is compressed before its combustion without supplying any illustration or referring to any working model. All four-stroke engines follow the sequence of intake, compression, power, and exhaust strokes (fig. 2.2). Beau de Rochas allowed his patent to lapse because of the nonpayment of fees and did not challenge Otto's four-stroke design when it was first commercialized during the late 1870s. Not until 1884, when a patent attorney unearthed the original 1862 pamphlet, was Otto's patent contested, and although it owed nothing to the de Rochas design, it lost its German priority in 1886 but retained its British rights.





**Figure 2.2**

The four strokes of an Otto/Beau de Rochas cycle, corresponding to the four phases of the pressure-volume diagram.

While Beau de Rochas, a skilled and experienced engineer (and Lenoir's friend), took no steps to convert his ideas into practical products, Nicolaus August Otto (1832–1891; [fig. 2.3](#)), who had no technical background (he was a traveling salesman for a wholesale food company) when he became fascinated with Lenoir's engine, dedicated himself to designing and commercializing progressively more advanced internal-combustion

machines, developed the first four-stroke engine despite the doubts of his experienced production manager (who later went on to make, independently, its first gasoline-powered version), had it promptly patented, and saw it manufactured in large series both in Germany and abroad.



**Figure 2.3**

Nicolaus A. Otto, the inventor of two- and four-stroke gas-fueled internal combustion engines (from Abbott 1934).

First he persuaded Eugen Langen (1833–1895), owner of sugar-refining factory, to invest in a new company (N. A. Otto & Cie, formed in 1864) whose first commercial product was a two-stroke atmospheric (noncompression) engine that was patented in 1866 in Germany and in 1867 in the United States (Langen 1919; Sittauer 1972). Otto's heavy and noisy engine was more than twice as efficient as other gas engines displayed at the Paris Exhibition in 1867, where it won a Grand Prix. Its

serial production started in 1868, and four years later the company was renamed Gasmotorenfabrik Deutz AG (named after the Cologne suburb where it was relocated), and nearly one and half centuries later Deutz AG remains one of the world's leading engine makers (Deutz 2009).

Gottlieb Daimler (1834–1900), an experienced mechanical engineer, became the company's production manager, and he hired Wilhelm Maybach (1846–1929) to head the design department. Two of the three designers of the first gasoline engine thus gained their experience in Otto's company. Their new noncompression engine was introduced in 1874 and had an efficiency of about 10 percent, but the tenfold expansion of gas that made this performance possible required a cylinder that was nearly 4 m tall. Although the engine was much heavier (its mass-to-power ratio was about 900 g/W) than the best contemporary steam engines, it sold well not only in Germany but also in France, the United Kingdom, and the United States.

Otto's aspiration was to build and to patent a compressing engine, and he succeeded doing that by the spring of 1876. The engine's two innovations were four-stroke operation and stratified combustion. The first innovation soon became an engineering norm, the second one took nearly a century to be commercialized. The idea of injecting air alone before introducing the fuel-air mixture to create a lean charge near the piston and hence a gradual burning of the fuel was adopted in the 1970s to lower the emissions of hydrocarbons and nitrogen oxides in exhaust gases. Honda's compound vortex-controlled combustion (CVCC, an acronym that gave the Civic its name) engine, introduced in 1973, has been perhaps the most acclaimed form of a stratified-charge engine (Bishop and Jorgensen 1981).

Compression gave Otto's engine some superior attributes. Its overall thermal efficiency was about 17 percent, while its piston displacement was reduced by 94 percent compared to a noncompression engine of the same power and its mass-to-power ratio was lowered by nearly 70 percent to about 250 g/W, making it lighter than similarly-sized (that is, very small) steam engines. A typical 6 kW (8 hp) machine worked with 2.6 to 1 compression, a 9 to 1 air-to-fuel ratio, a 210 mm bore, and a 350 mm stroke, and it ran at 160 rpm (Clerk 1909). The next critical step, the design and development of a gasoline-fueled engine, also took place in Germany. After he left Otto's company in 1882, Daimler set up a workshop in a Stuttgart suburb and with Maybach set out to build a powerful lightweight engine that was fueled by gasoline (Walz and Niemann 1997).

This was a superior fuel compared to coal gas. Its energy density (lower heating value) of 33 MJ/L (or more than 43 MJ/kg) is about 1,600 times the energy density of the illuminating gas and its low flashpoint ( $-40^{\circ}\text{C}$ ) made it ideal for easy starting. By 1883, Daimler and Maybach had a prototype of a high-revolution (about 600 rpm) gasoline-fueled engine with a surface carburetor and hot-tube ignition. Two years later, in November 1885, they used its air-cooled successor to power the world's first motorcycle, and in March 1886 they mounted a larger (0.462 L, 820 W), water-cooled version of the engine on a standard wooden-wheeled coach and took the first extended ride in 1887 (Walz and Niemann 1997).



**Figure 2.4**  
Karl Benz. Photograph courtesy of Daimler Konzernarchiv, Stuttgart.

Concurrently and entirely independently, their achievement was matched by Karl Friedrich Benz (1844–1929; [fig. 2.4](#)) whose mechanical workshop

was located in Mannheim, about 120 km from Stuttgart (Walz and Niemann 1997). Benz developed first (in 1883) a two-stroke gasoline-fueled, water-cooled horizontal engine with electric ignition, and after the expiry of Otto's patent he designed a four-stroke machine for which he obtained the German patent on January 29, 1886. Unlike Daimler and Maybach, he mounted it first on a three-wheeled carriage that was shown to the public on July 3, 1886 (fig. 2.5). The single-cylinder engine weighed only 96 kg, and it was less powerful (0.954 L, 500 W) and slower (250 rpm) than Daimler and Maybach's machine.



**Figure 2.5**

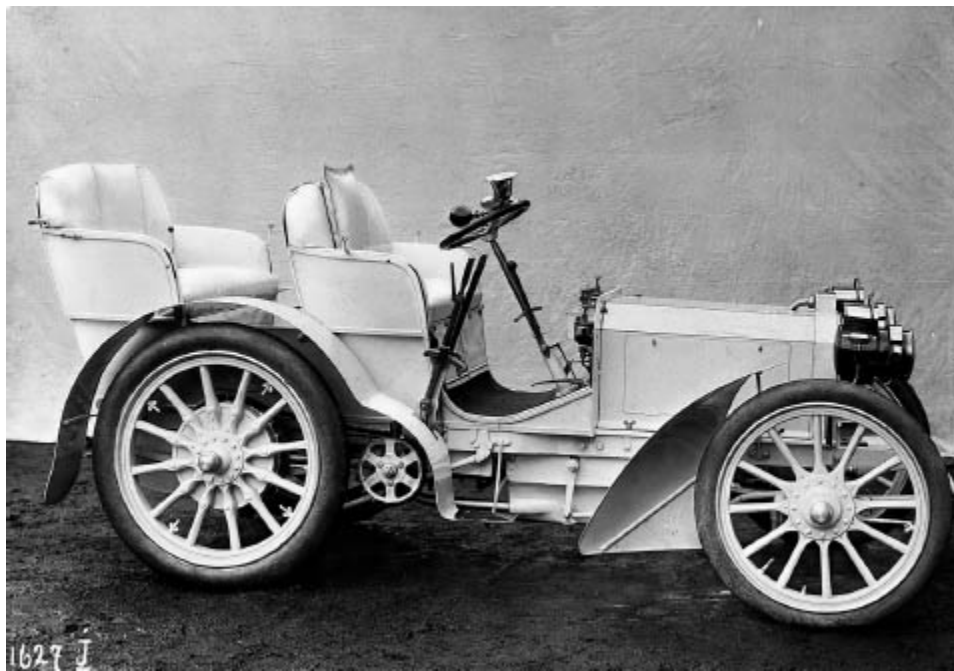
Benz's 1886 gasoline-powered three-wheeler, shown on the cover of his company's first catalog (published in 1888).

Reproduced courtesy of Daimler Konzernarchiv, Stuttgart.

These pioneering developments were followed by a period of steady technical improvements but limited commercial expansion. In 1889, Daimler and Maybach marketed a new two-cylinder V engine displacing 0.565 L and running at 920 rpm. In 1890, they built their first four-cylinder

machine, and in 1895, their 4.5-kW engine, with a mass-to-power ratio of less than 30 g/W, won the Paris-to-Bordeaux race, averaging 24 km/h over nearly 1,200 km (Beaumont 1902).

The first true modern automobile went on sale in 1901: Mercedes 35 had a powerful four-cylinder engine (5.9 L, 26 kW, or 35 hp) that ran at 950 rpm (Smil 2005). Its weight was reduced to just 230 kg thanks to an aluminum block, and the larger cooling surface of a new honeycomb radiator (still a standard more than a century later) halved the volume of coolant. The engine's mass-to-power ratio was thus kept below 9 g/W, 70 percent better than the best Daimler design of just five year earlier. Soon after its release, the new car, now considered the prototype of all modern vehicles, set a new world speed record of 64.4 km/h (fig. 2.6).



**Figure 2.6**

Wilhelm Maybach's 1901 Mercedes 35, the prototype of a modern high-performance car. Photograph courtesy of Daimler Konzernarchiv, Stuttgart.

Even at that point, the dominance of Otto-cycle gasoline engines was not assured as steam-driven cars and electric cars were preferred by many drivers (Volti 1990; Smil 2005). But their apparent competitiveness could not last. Steam cars took a long time (up to twenty minutes) to start, and their small boilers could not keep an adequate steam reserve, had a short operating range, and required careful monitoring and manipulation. The

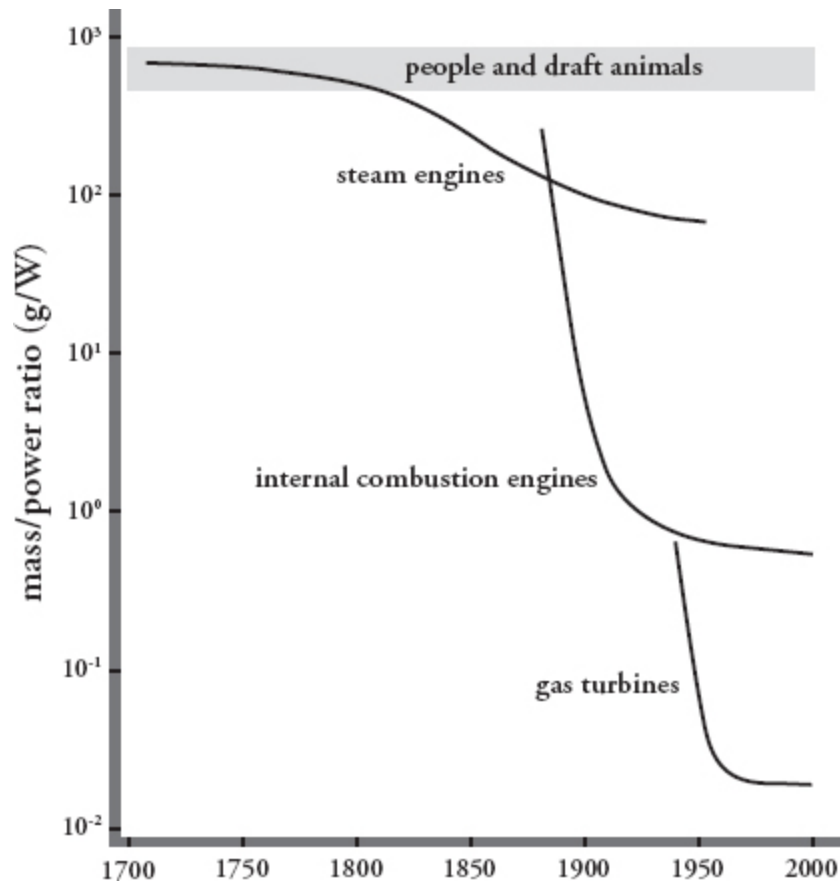
future of electric cars looked much more promising because the cars were clean and quiet, devoid of any hot steam or flammable fuel, and easy to start without any need for laborious (and dangerous) hand-cranking. By 1901, Pope's Electric Vehicle Company was both the largest maker and the largest owner and operator of motor vehicles in the United States (Kirsch 2000) but heavy batteries, limited speeds, and short ranges were the undoing of the electrics, and by 1908, the contest was over with the introduction of Henry Ford's Model T (Ford Motor Company 1908; Model T Ford Club of America 2008).

### **Rapid Maturation and the Inherent Limits of Gasoline Engines**

The history of sparking, four-stroke, internal-combustion engines is remarkable because of a steep learning curve that transformed the pioneering heavy horizontal machines into increasingly lighter, more powerful, more efficient prime movers that were suitable for mobile applications. This transformation can be revealingly traced by their declining mass-to-power ratios. Comparisons with human and animal exertion and with steam engines (the nineteenth century's dominant prime mover) illustrate these remarkable achievements. Humans are able to sustain work at the rate of 60–80 W and hence need about 1,000 g/W of useful labor. Draft animals have similarly high mass-to-power ratios, too high to energize the rapid longdistance transport of loads on land or the fast movement of heavy cargoes on water (fig. 2.7).

The first noncompressing coal-gas-fueled internal-combustion engines of the mid-1870s with a mass-to-power ratio of about 900 g/W were as heavy as animate prime movers and much heavier than steam engines of the same capacity. In 1876 Otto's first practical four-stroke design rated about 270 g/W; by 1890 the best Daimler-Maybach gasoline engine was down to about 45 g/W; in 1901 Maybach's famous first Mercedes rated 8.5 g/W (Wood 1985); and the four-cylinder engine of Ford's Model T, introduced in 1908, weighed eventually less than 5 g/W. By the 1960s, the mass-to-power ratio of car engines had stabilized at around 1 g/W (for example, by 1965, the Mustang rated 1.1 g/W, and the Austin Mini 1 g/W), which means that fewer than 10 percent of the total 1890 to 1970 improvements took place before World War I (fig. 2.7).





**Figure 2.7**

The mass-to-power ratio of prime movers—from draft animals to internal-combustion engines (based on Smil 2008).

Similarly, reciprocating aeroengines improved rapidly, and their use spread from artisanal manufacturing of a single engine or a few units before 1905 to many thousands of machines in mass serial production by the end of World War I. The engine that powered the first flight was a horizontal four-cylinder (in-line) machine designed by Wilbur and Orville Wright and built by their bicycle mechanic Charles Taylor in 1903 in their workshop in Dayton, Ohio, to deliver 6 kW (8 hp). Its eventual performance was 12 kW, and this and a weight of 91 kg pushed the mass-to-power ratio as low as 7.6 g/W. By 1917 the Liberty, the most popular American engine of World War I, had a mass-to-power ratio just above 1 g/W (Dickey 1968).

World War II brought further improvements: Wright R-3350 radial engines used on B-29 (Superfortress) bombers had mass-to-power ratios of just 0.74 g/W, less than a tenth of the Wrights' pioneering machine (Gunston 1986). The mass-to-power ratio of Otto-cycle gasoline-fueled

engines had thus improved roughly a hundredfold in just forty years, and the expansion of automobile ownership, truck transportation, and commercial and recreational flying attested that these machines were eminently suitable for mobile applications. Even so, these spark-ignited engines had several inherent drawbacks that would make them less than perfect prime movers of a globalized economy and that worked against their adoption for high-volume marine shipping, for long-distance trucking, and for all longer intranational and intercontinental flights.

I begin the list of drawbacks with gasoline, the optimum fuel for Otto-cycle machines. This lightest (with a specific density between 720 and 780 g/L) and most volatile of all refined fuels used to be the least voluminous and hence the most expensive major product of crude-oil distillation. Simple thermal distillation (the separation of oil fractions by heating) of typical (that is, medium-density and heavy) crude oils that dominate the global market would yield only 10 to 15 percent of the charged volume as the lightest fraction. This low yield became a great concern after growing car ownership in the United States led to a rapidly increasing demand for gasoline (between 1907 and 1915 that demand rose fivefold). Without any means to increase the gasoline yield of the refining process, the worldwide extent of driving and flying powered by the lightest liquid hydrocarbon fuel would be greatly restricted.

The first practical way to increase that yield (and lower the cost) was patented in 1913 by William M. Burton (1865–1914), who used the thermal cracking of crude oil (a combination of heat and high pressure) to break heavier hydrocarbons into lighter fractions. A better solution for producing more gasoline arrived soon through catalytic cracking and hydrocracking (Meyers 2004). The first process, patented by Almer M. McAfee in 1914 and commercially available since 1923, worked by heating crude oil in the presence of aluminum chloride, and it boosted the gasoline yield by as much 15 percent compared to thermal cracking.

But this was a wasteful and hence expensive process because the catalyst could not be recovered and reused. In 1936, the first catalytic cracking unit that allowed for the recovery of the catalyst while producing high-quality gasoline was designed by Eugène Houdry (1892–1962). Catalyst replacement and regeneration required a temporary shutdown of the refining operation, a drawback that was solved by Warren K. Lewis and Edwin R. Gililand by circulating the catalyst between the reaction and the

regeneration vessels on a moving bed, and even higher yields of high-octane gasoline were achieved when Standard Oil suspended a powdered catalyst in the air stream.

This process of fluid catalytic cracking was later greatly improved with the addition of synthetic zeolites—crystalline aluminosilicates that had a uniformly porous structure and that provided an exceptionally active and stable catalyst for cracking heavy hydrocarbons. The last important innovation came in the 1950s, when the Union Oil Company developed hydrocracking, which combines catalysis at temperatures above 350°C with hydrogenation at relatively high pressures. All of this comes at a cost, and catalytically produced gasolines (mixtures of compounds with four to twelve carbons) became the most expensive commodities of the refining process.

Diesel fuel is a blend of compounds with eight to twenty-five carbons that are obtained by atmospheric distillation (light gas oil that boils between 204 and 343°C) as well as from cuts produced by hydrocracking, fluid catalytic cracking, viscosity breaking, and coking. Its lightest category (U.S. number 1 diesel fuel) is dominated by molecular chains with nine to sixteen carbons, while the heavier fraction (number 2, the primary fuel for diesel engines) has molecules with ten to twenty carbons, and it used to contain two to three times more sulfur than do the lighter distillates. Diesel fuel (or diesel oil) is usually the second most important product of modern refineries. In the United States, it has recently accounted for about 18 percent of the total, compared to 46 percent for gasoline and nearly 10 percent for jet fuel (kerosene). For decades, US diesel fuel used to be less expensive at the retail level than gasoline, an added advantage in operating inherently more efficient diesel engines.

But by the end of 2006, the U.S. diesel fuel was nearly 9 percent more expensive than gasoline (average price for all grades); a year later the difference was 9 percent; by the end of 2008, it was 38 percent, but by the end of 2009 the difference narrowed to just a few percent. This price reversal took place because of the combination of limited U.S. refining capacities, growing worldwide demand for the fuel (mainly because of its rising use in passenger cars in Europe and because of heavy transportation demand for shipping and trucking in China and India), and to a large degree, because of much stricter limits on the fuel's sulfur content (Energy Information Admin. 2007a). New U.S. Environmental Protection Agency

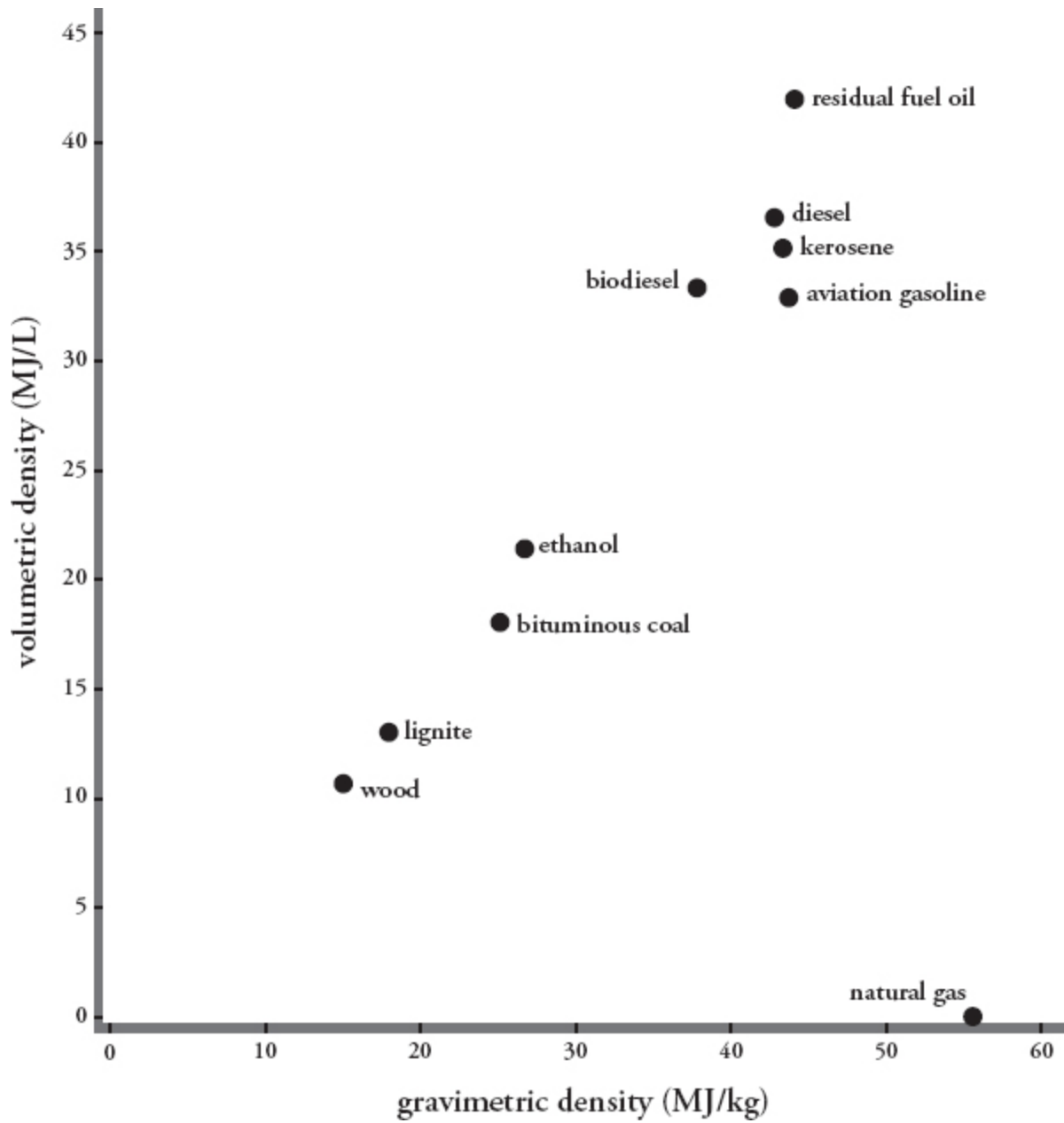
standards mandated that by June 1, 2006, 80 percent of all diesel fuel for highway use had to be ultra-low-sulfur diesel (ULSD) fuel with no more than 15 ppm of sulfur, a huge reduction from the previous limit of 500 ppm of sulfur for low-sulfur diesel.

Retail price of liquid fuels has always been strongly influenced by taxation. For a long time, taxes have been the largest component of diesel fuel price in the United Kingdom, Germany, Italy, Sweden, and Norway, but the fuel has been taxed much less in most other European countries, the United States, Canada, and Japan. Consequently, wherever diesel fuel retains its cost advantage over gasoline, the difference has nothing to do with the inherent qualities of crude oils and the cost of refining but is a result of differential taxation. All of these price comparisons have been based on volume and not on energy content as they ignored diesel fuel's higher energy density. Molecular weight of compounds making up diesel fuel is roughly double that of hydrocarbons in gasoline (about 200 versus 100 to 105) and their viscosity is five to ten times higher than that of the lighter compounds present in gasoline. The specific density of diesel fuel is nearly 14 percent higher than that of a typical gasoline (820 to 850 g/L 720 to 750 g/L), while the energy density of its constituent compounds is very similar to that of the hydrocarbons that make up gasoline. Consequently, its energy density per volume is about 12 percent higher, almost 36 MJ/L versus approximately 32 MJ/L, both being the lower heating values. The respective higher heating values are approximately 39 and 35 MJ/L ([fig. 2.8](#)). This means that a unit of energy in diesel fuel costs less than the unit of energy in gasoline as long as the former is not more than 12 percent more expensive than the latter. It also means that ships that are fueled by diesel fuel could travel (everything else being equal) 12 percent farther than vessels with equally large stores of gasoline. But everything else is not equal because Otto engines are inherently less efficient converters of chemical energy into mechanical energy than are the diesel engines.

Marine diesel engines—by far the most powerful reciprocating machines—are designed to run primarily on residual fuel oil (RFO) known also by such synonyms as heavy fuel oil (HFO), fuel oil number 6, and bunker fuel. These dark brown to black residual oils with a strong tarlike odor are the heaviest of all distillates (with a specific gravity of 0.960 to 0.985 at 15°C), they have more complex composition and contain more impurities than do the lighter distillates (their sulfur content can be as high as 4.5 percent), and

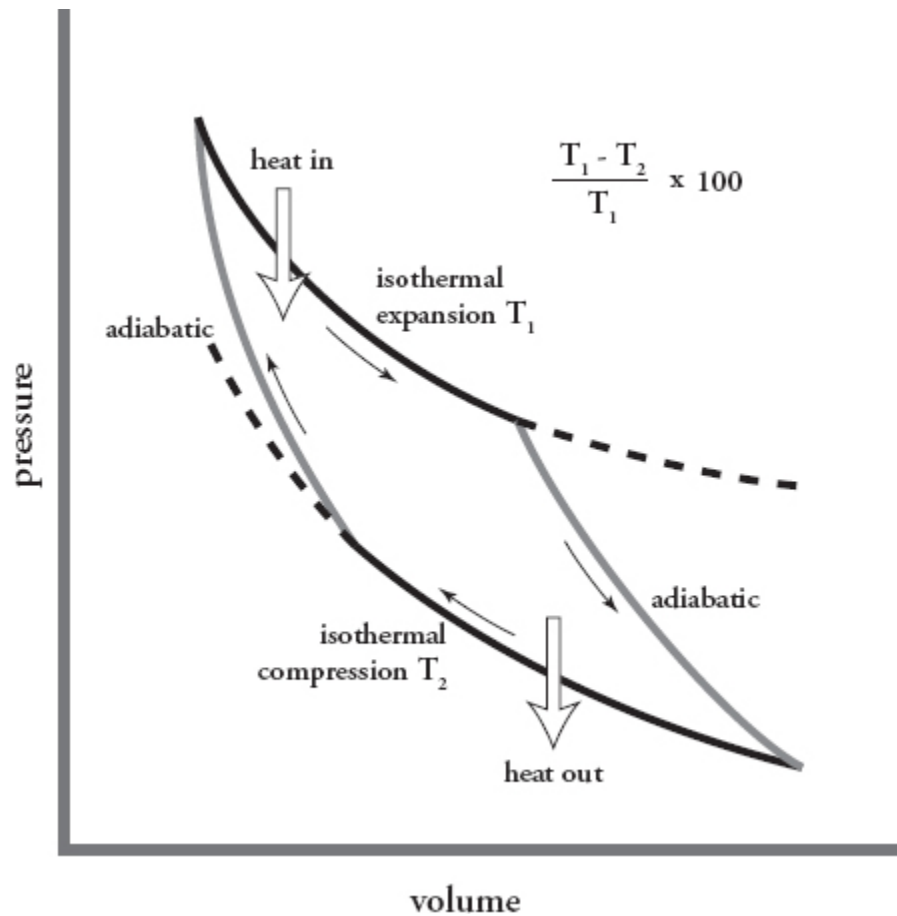
their most viscous kinds have to be stored in warmed containers and heated prior to pumping. Fuel oil number 6 is the residual product that is most commonly used by large diesel-powered ships. The higher heating value of this fuel is 43 MJ/kg or as much as 42.35 MJ/L, making it the most energy-dense fossil fuel that is in common use (fig. 2.8). But large modern marine diesels can also run, at one extreme, on unrefined crude oil and, on the other extreme, on any plant oil or waste cooking oils, and they can be also configured for the dual burning of liquids and gases, both natural and synthetic.

The maximum possible efficiency ( $\eta$ ) of any heat engine that would operate reversibly without any increase of entropy is equal to 1 minus the quotient of the machine's lowest ( $T_1$ ) and highest ( $T_h$ ) operating temperatures expressed in degrees Kelvin:  $\eta = 1 - T_1/T_h$ . This ideal cycle was described for the first time by Sadi Carnot (1796–1832) and carries his name. The Carnot cycle is an entirely theoretical concept because no real engine can work reversibly and transfer heat isothermally—that is, without any change of temperature (fig. 2.9). A 100 percent efficient engine would have to have its cold end at absolute zero. The maximum efficiency of an ideal Otto cycle is  $\eta = 1 - r^{1-\gamma}$ , where  $r$  is the engine's compression ratio (the ratio between the maximum and minimum volume of the combustion chamber) and  $\gamma$  is the heat-capacity ratio. With a compression ratio of 4 to 1 (typical of the earliest engines), the maximum would be about 40 percent. With  $r = 8$  to 1 – 10 to 1 (typical of modern engines), the peak would be 55 to 60 percent.



**Figure 2.8**

A comparison of the volumetric and gravimetric densities of common fuels shows the advantages of diesel fuel and kerosene for mobile applications (plotted from data in Smil 2008).



**Figure 2.9**  
A Carnot cycle graph (based on Smil 2008).

As with any heat engine, in practice only a fraction of this maximum is attainable because losses due to cooling and friction roughly halve that theoretical total. Lenoir's earliest atmospheric engines had efficiencies of less than 5 percent, the Otto-Langen machine of 1867 eventually reached up to 11 percent, Otto's first four-stroke engine of 1876 had its maximum at about 14 percent, and maxima of 20 percent were attained by the beginning of the twentieth century. The peak performance of today's well-maintained and appropriately operated modern engines is about 32 percent, but typical rates for machines that have been in everyday use for some time is still no higher than 20 to 25 percent—that is, only a fifth or a quarter of a fuel's chemical energy is transformed into kinetic energy supplied by the engine (van Basshuysen and Schäfer 2004).

In contrast (as I explain in detail in [chapter 3](#)), even during its very first certification tests in February 1897, Diesel's engine was more than 25

percent efficient, and subsequent improvements raised the rate to 41 percent by 1911, approximately twice as high as the usual peak efficiencies of contemporary gasoline-fueled engines (Clerk 1911). The best efficiencies of today's largest marine diesel engines are in excess of 50 percent (Wärtsilä 2009a; MAN 2009) while the peak performance of spark ignition engines (large, MW-sized stationary natural gas-fueled combined heat and power machines) is just over 40 percent. Moreover, diesel engines can burn a fuel of the lowest quality whose high sulfur content is too high to be used in land transportation. The higher compression ratio of diesel engines is the principal reason for this difference, but it is not easy to operate gasoline-fueled engines under higher pressure.

As the ignition wave propagates downward, high pressure and high temperature lead to a spontaneous combustion of the fuel, which sends a pressure wave in the opposite direction, resulting in a violent, engine knock. The only way to avoid this detonation (knocking or pinging) in the early gasoline-fueled engines was to hold the compression ratio below 4.3 to 1, a restriction that limited the engine efficiency. By 1921, a General Motors team led by Charles F. Kettering identified ethanol as an effective antiknocking ingredient (Lavine 1960). But during the 1920s, large-scale production of ethanol was too expensive, and bromine and iodine alternatives were even more costly.

A General Electric team led by Thomas Midgley confirmed on December 9, 1921, that tetraethyl lead was a highly effective antiknocking agent, even when added at concentrations as low as 1/1000 of the fuel's volume (Midgley 2001). Leaded gasoline was marketed for the first time in February 1923, and its use allowed engineers to raise the compression ratio to the modern range of 8 to 1 up to 10 to 1. But as is well known, the use of this additive has come with substantial environmental and health costs. Lead's effect on ecosystems and human health (as other heavy metals do, it poisons the central nervous system and results in the deterioration of mental capacities) eventually led to the phaseout of leaded gasoline that began in the United States in 1975 and was completed by 1990 (Kovarik 2005). Diesel engines, with compression-induced spontaneous combustion, do not need any sparking and hence have no problem with untimely detonation.

Gasoline-fueled spark-ignition engines have another limitation for which there has been no effective engineering solution: they are not practical in very large sizes. That is why their maximum displacement is about 10 liters



and the highest rated power for an automotive engine (McLaren F1 LM) is 500 kW (680 hp). More powerful Otto-cycle four stroke engines are available for stationary applications (electricity generation, powering compressors): for example, MWM offers machines rated up to 3.6 MW and GE Energy's most powerful range of engines has electrical output of up to 3 MW. But all of these machines are fueled by natural gas or biogas, not by gasoline, and even these largest spark-ignition engines are too small for many industrial applications, which can be readily serviced with diesel engines whose sizes now range over four orders of magnitude, from less than 10 kW (for small Yanmar outboard motors) to more than 80 MW (for the largest machines powering fast container ships). And regardless of their rated capacity, diesel engines have two other much appreciated advantages: they are admirably reliable and extremely durable.

The diesel engines that power heavy trucks can last easily more than 200,000 km before they need an overhaul, and some well-attested longevities are longer than 1 million km on the road (Charles River Associates 2000). Similarly, large diesels powering heavy freight locomotives can go for six years before an overhaul, and nothing better demonstrates the reliability of large two-stroke marine diesels that power all tankers, other bulk cargo carriers, and container ships than the fact that none of these ships has any backup engines to be used in the case of failure. Mechanical problems do happen during voyages, but in an overwhelming majority of cases, they can be resolved by a small crew of mechanics that is always onboard.

High-performance reciprocating aeroengines that are fueled by leaded gasoline made commercial aviation possible, but they have the same cost disadvantage when compared to gas turbines (Chevron Products Corporation 2000). At 0.81 (g/cm<sup>3</sup> kerosene has a specific density that is about 13 percent higher than that of aviation gasoline (0.715 g/cm<sup>3</sup>), and with only marginally lower energy content (43.3 MJ/kg versus 43.7 MJ/kg for aviation gasoline) (see [fig. 2.8](#)), a plane can fly at least 10 percent farther with the same volume of fuel. The heavier fuel is also cheaper than gasoline and has lower evaporation losses at high altitudes. It is also safer, having a lower risk of fire during ground handling and producing more survivable crash fires. Gasoline-fueled long-distance aviation would not be just more expensive and less safe but also more uncomfortable and more tedious.

The vibration that is produced by piston strokes is a major source of discomfort and potentially a serious safety matter. It is tolerable as long as the piston pulses are virtually identical, but misfiring sparkplugs, leaky valves, and worn parts aggravate it, shaking the plane and eventually loosening rivets and pivots and also causing dangerous pilot fatigue (U.S. Air Force 1948; Scanlan and Rosenbaum 1951). Constant vibration was made worse because of the duration of long-distance flights and low cruising altitudes. The limited power of reciprocating engines kept the cruising speeds well below 500 km/h. The Douglas DC-3—the most common and most durable piston-powered commercial airplane and introduced in 1935 (fig. 2.10)—cruised at just 240 km/h (the landing speed of modern jetliners) at an altitude of about 6 km (its ceiling was 7.3 km), well within the most active layer of the troposphere, where airplanes encounter frequent turbulence (Taylor 1989). Four Wright Twin Cyclone engines of the Boeing 31 Clipper, first used in 1938 on trans-Pacific routes by Pan American World Airways, made it possible to fly to Asia with speeds up to 320 km/h.



**Figure 2.10**

A Douglas DC-3, the most successful piston-powered airplane in history. Photograph courtesy of American Airlines.

And even the four-engine Super Constellation, the fastest and the most powerful post-World War II piston-powered airliner, could not manage more than 520 km/h at the same altitude (Taylor 1989). In contrast, the first passenger jet, the British Comet, cruised at about 725 km/h, and today's jetliners cruise at more than 900 km/h at maximum altitudes of up to 12,500 m (Cowell 1976). Trans- and intercontinental flights are typically two to nearly four times (when counting the refueling stops that were necessary on long flights) faster than they were in the piston-engine era. And because the rapid rotary motion of gas turbines produces much less vibration than the reciprocating motion of piston engines and because jets can fly in the highest reaches of the troposphere (well above all but a small fraction of the atmospheric turbulence), jet flights are incomparably smoother.

There is no doubt that the global trade in raw materials, foodstuffs, and manufactured goods would have grown during the latter half of the twentieth century even if ships continued to be powered only by steam engines. Similarly, there is no doubt that the extent and frequency of intercontinental flights that were powered by high-performance piston engines would have expanded much beyond its pre-World War II level. But there is also no doubt that neither global trade nor intercontinental flights activity would have reached such levels of unit capacity, speed, reliability, convenience, and low prices as have been possible because of diesel engines and gas turbines.

The eventual outcome of these relatively rapid developments—the global dominance of these efficient prime movers and their now indispensable roles in sustaining economic globalization, the rising interdependence of nations, and high personal mobility—could have been a sound theoretical expectation, but the road to the technical supremacy and economical indispensability of these two prime movers was not (particularly in the case of diesel engines) a matter of inevitable, autonomous advances. The commercialization and worldwide diffusion of diesel engines and gas turbines were governed at least as much by national peculiarities (most notably by the early German lead in engine design and by America's post-World War II dominance of aerospace design) as by general historical circumstances and technical and economic imperatives.

# 3

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## Diesel's Engine

Noch kein menschlicher Motor hat das erreicht, was der meine ergab, und so habe ich denn das stolze Bewusstsein, in meinen Fache der Erste zu sein.

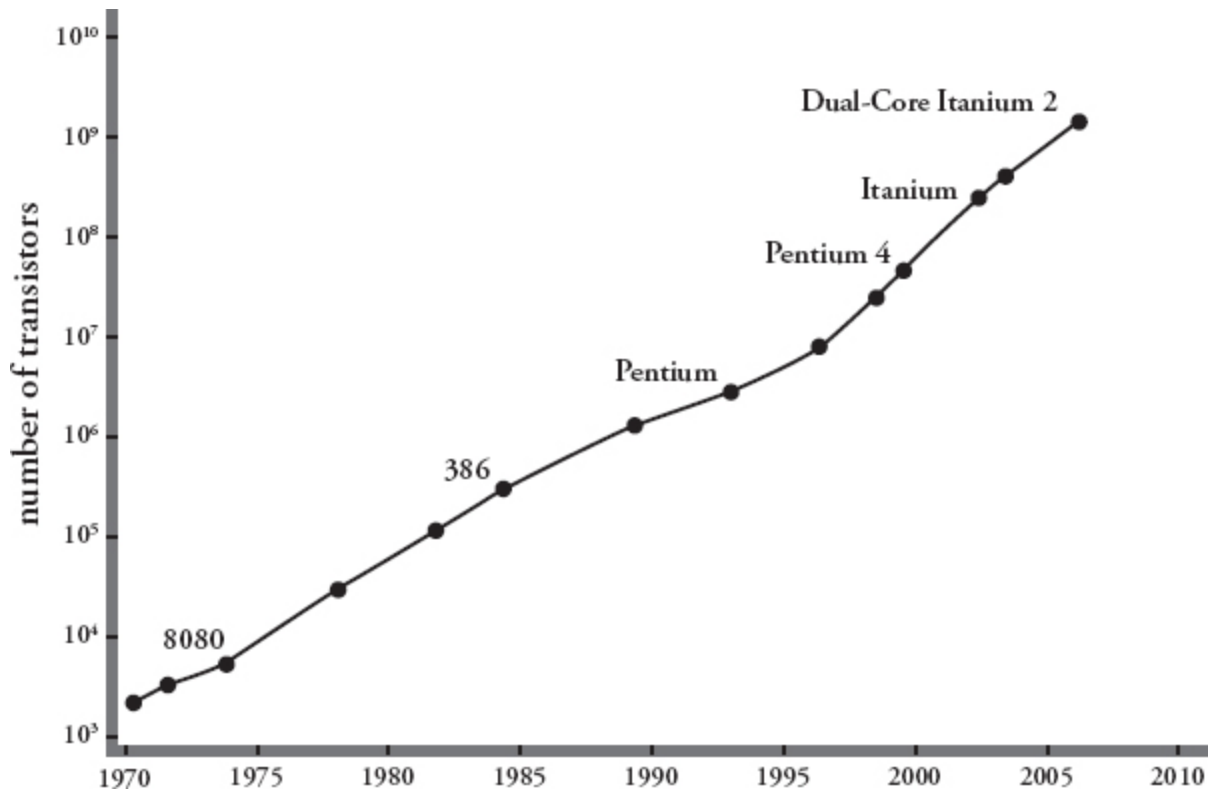
[Nobody's engine design has achieved what mine has done, and so I can have the proud awareness of being the first one in my specialty.]

—Rudolf Diesel in a letter to his wife, February 1897

Because Rudolf Diesel's engines (generically, *diesel engine* or simply *diesel*) power many road and off-road vehicles, rail locomotives, and ships, nearly everybody knows at least the name. Europeans are much more familiar with diesels than Americans because they use them as reliable and considerably less expensive alternatives to gasoline-fueled automotive engines: nearly half of all European passenger cars are now diesel-powered. The American public knows the diesel engine as the prime mover of trucks and agricultural and heavy off-road machinery, but it has been wary of using it in passenger vehicles. In 2005, merely 2 percent of all cars, pickups, and sport utility vehicles in the United States had diesel engines. Those familiar with cargo shipping know that diesels power nearly all intercontinental trade (by energizing massive container ships, crude-oil tankers, and other bulk-commodity carriers) as well as almost all long-distance continental transport of goods (by freight trains, barges, and intercity trucks).

But how many people would be able to name the engine's key specific features and list the principal reasons for its claim to excellence and for its dominance as the prime mover of long-distance ocean shipping and heavy road and rail transport? Those with a modicum of technical understanding would point to its distinct mode of ignition or to its relatively high fuel-conversion efficiency—but even they would not be likely to rank the machine among the indispensable, iconic artifacts of modern civilization. Diesel's engine is not alone in this respect: other critically important

machines work in similar obscurity. In contrast, those near-miraculous accomplishments of solid-state electronics—its rapid trajectory from the first transistors in the late 1940s to the first microprocessors in the early 1970s, personal computers in the 1980s, and the Internet in the 1990s—have made miniature microchips (rather than bulky mechanical contraptions) perhaps the most admired icons of technical modernity.



**Figure 3.1**

Moore's law predicted a continuous doubling of the density of transistors on a microprocessor (the actual numbers of transistors per die are shown in parentheses) (based on data in Intel [2007]).

I think it is a safe assumption that a poll would show that more people are familiar with Moore's law (originally stating that the number of transistors on a microchip will double every twelve months and later revised to twenty-four months) (Moore 1965; Intel 2003; [fig. 3.1](#)) than with the intricacies of Diesel's machine. Most people who think that our world would be unimaginable without microchips do not think of steam turbogenerators (see [fig. 2.1](#)) as the quintessential machines of modernity. Yet without them, most microchips would be useless because those huge machines are responsible for generating four-fifths of the world's electricity

(81 percent in 2005) (Energy Information Admin. 2008) in large fossil-fueled and nuclear plants. The rest of the world's electricity comes largely from hydroturbines and gas turbines, and a very small but rapidly rising share is generated by wind turbines and photovoltaic cells.

Until the 1950s, a complex civilization had functioned quite satisfactorily without any help from solid-state electronics. The first transistorized consumer goods appeared in the mid-1950s, and the first transistorized computers came in 1959 with IBM's Stretch and Sperry Rand's LARC. The world's first universal microprocessor was a tiny rectangle of  $3 \times 4$  millimeters that was capable of sixty thousand operations per second and that was released in November 1971 (Intel 2001). But the world of the 1950s and 1960s depended, as it still does today, on the truly indispensable work of steam turbogenerators. Similarly, most people who see the now ubiquitous products of solid-state electronics as the most representative expression of technical modernity would not rank Diesel's engine among the handful of machines whose work truly underpins our economies in ways that are much more fundamental than the contributions of all those appealing electronic gadgets. A key goal of this book is to remedy this appreciation deficit.

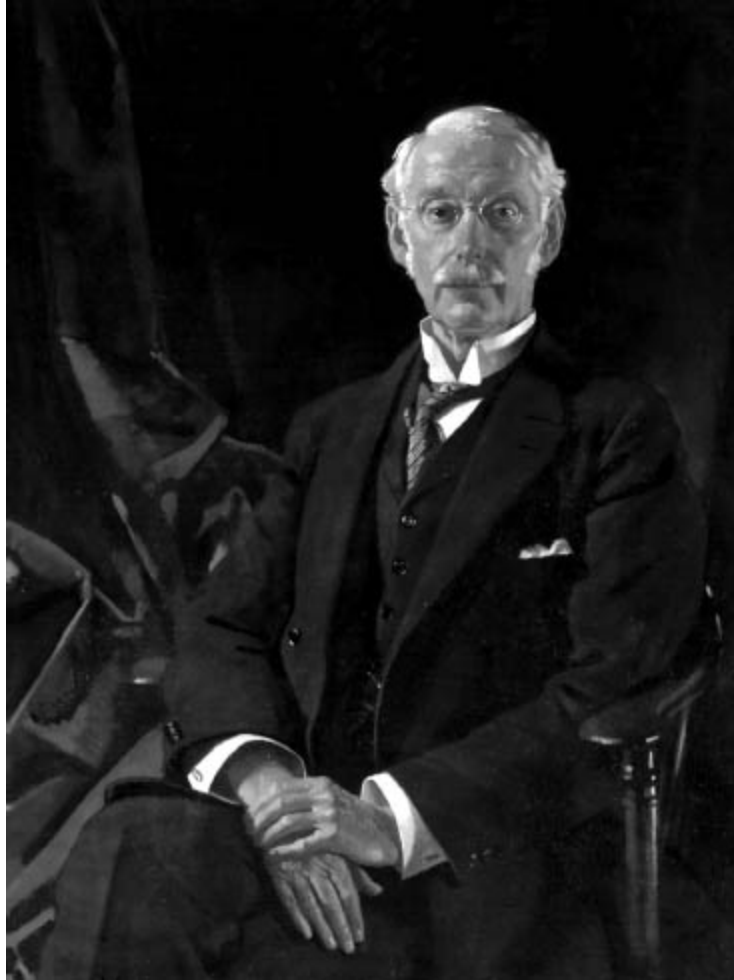
## **The Engine's Beginnings**

Diesel's engine shares a much more fundamental trait with the steam turbogenerator than just its low status in the public's perception of technical advances. It belongs to that rare category of pioneering nineteenth-century inventions whose idea arose from theoretical analyses rather than from experimentation with actual designs. This contrasted with the first generation of fundamental technical advances, which made possible a period of unprecedented economic expansion that became commonly, if arguably, known as the first industrial revolution and whose (highly variable) dating spans most often 1750 to 1850. Those advances were based overwhelmingly on incremental improvements that were derived from practical experience and experimentation with existing designs. An improved design of Newcomen's highly inefficient steam engine by James Watt is the best known example in this category. Similarly, Benoit Fourneyron's pioneering designs of a radial-flow water turbine and its first

installation in the 1830s were based on long experience with shaped horizontal waterwheels (Crozet-Fourneyron 1924).

As already noted (in [chapter 1](#)), during the first sixty years of the nineteenth century, many inventors (more than a dozen) patented and demonstrated inefficient noncompression internal-combustion engines whose crude design appeared first during the closing decades of the eighteenth century (Cummins 1989). In contrast, during the early 1880s, the miraculous decade of the second industrial revolution, Charles Algernon Parsons (1854–1931) set out to design a steam turbine—the machine that eventually became the most powerful commonly used prime mover of modern civilization and an indispensable means of generating most of the world’s electricity—because the advances in theoretical thermodynamics made it clear to him that it could be done ([fig. 3.2](#)). Similarly, Diesel’s engine had its origins in a scientific understanding of thermodynamics, and Diesel’s own account of his invention, written twenty-five years after the event and a month before his death, recounts how he got the idea for a superior engine as a young university student and how the determination to make it a reality had never left him (Diesel 1913, 1–2):

When my esteemed teacher, Professor Linde, explained to his audience at the Munich Polytechnic in 1878, during his lecture on thermodynamics, that the steam-engine transforms into effective work only 6–10% of the heat value of its fuel, when he explained Carnot’s theorem, and pointed out that with isothermic changes of condition all heat conducted to a gas would be converted to work, I wrote in the margin of my college notebook: “Study whether it is not possible to realize in practice the isotherm?” Then and there I set myself the task! That was still no invention, not even the idea of one. Thereafter the wish to realize the ideal Carnot cycle dominated my existence. I left the school, went into practice, had to win a position in life. The thought pursued me incessantly.



**Figure 3.2**

Charles Algernon Parsons, the inventor of the steam turbine—the prime mover that still produces most of the world’s electricity.

This 1922 portrait by William Orpen is reproduced courtesy of the Tyne and Wear Museums, Newcastle upon Tyne.

While both Parsons’s and Diesel’s inventions were the products of converting advanced scientific knowledge into machines with unprecedented attributes, they came to differ substantially in achieving the initially stated objective. Parsons had realized his intentions almost perfectly, and during his life he saw his machine rapidly displacing steam engines and completely conquering the new (and lucrative) industrial field of thermal electricity generation. In contrast, Diesel’s initial goal—to design an engine whose operation would conform closely to the ideal Carnot cycle—was impossibly ambitious, and the specifications given in his original patent could not be translated into a practical machine. This disparity

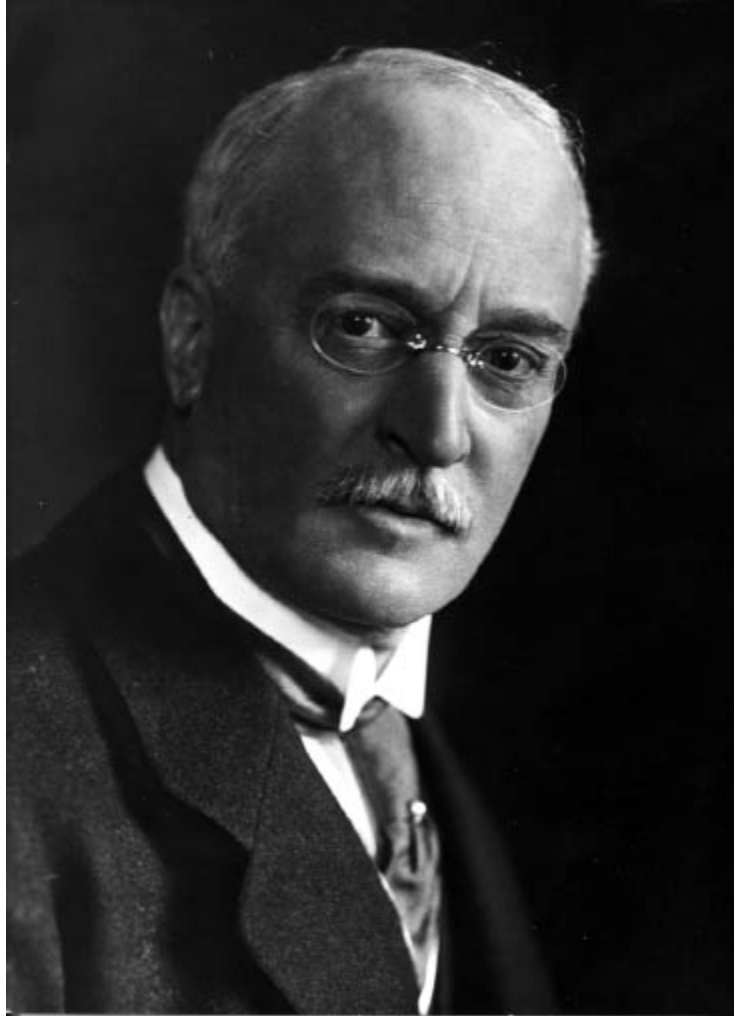


between an ideal design and eventual working machines generated a great deal of criticism during Diesel's life, some of it pointedly personal and unsparing. Such attacks had undoubtedly contributed to a further weakening of Diesel's always fragile health, but we will never know to what extent they contributed to his suicide.

He never talked to anybody about ending his life, and he did not leave any final note (fig. 3.3). During the last week of September 1913, he traveled from Frankfurt to Belgium. On September 27, he was in Brussels to visit a large Diesel engine factory owned by George Carels. On the 28th and 29th, he wrote several letters to his wife.

On the afternoon of September 29, he wrote again from Gent to his son Rudolf about the visit planned for the next day at the Ipswich Diesel engine factory, which was to be followed by a dinner in London's Royal Automobile Club, and just before the departure from Antwerp yet another letter to his wife. He boarded the *Dresden*, which was scheduled to arrive in Harwich next morning, with Carels and his chief construction engineer, Alfred Luckmann. They had a dinner together, walked on the deck afterward, and parted at about 10 p.m., when Diesel asked a steward to be woken at 6:15 a.m. When he did not show up for breakfast next morning, they knocked on his cabin, but there was no answer. The cabin was in perfect order but empty.

On October 10, a boat discovered a body, and the captain removed a few possessions (no papers were found) before committing it back to the sea. Rudolf and Eugen Diesel traveled to Belgium and identified their father's small box for sweets, his black *portemonnaie* with a few English and Dutch coins, a pocket knife, and a case for glasses with the mark of Diesel's Munich optician. Back in Munich, after they examined financial papers and statements, they concluded that their father left them in a hopeless financial situation and that the best they could do is to satisfy the creditors with the highest possible payments: they were instantly poor. Why did Diesel, proud of his rational approach to machines as well as to social problems, let his financial situation deteriorate? Why he did not confide to one of his old friends who could have helped (as Adolphus Busch said he was ready to do after hearing of Diesel's death)?



**Figure 3.3**  
Rudolf Diesel.  
Photograph from the MAN Bildarchiv.

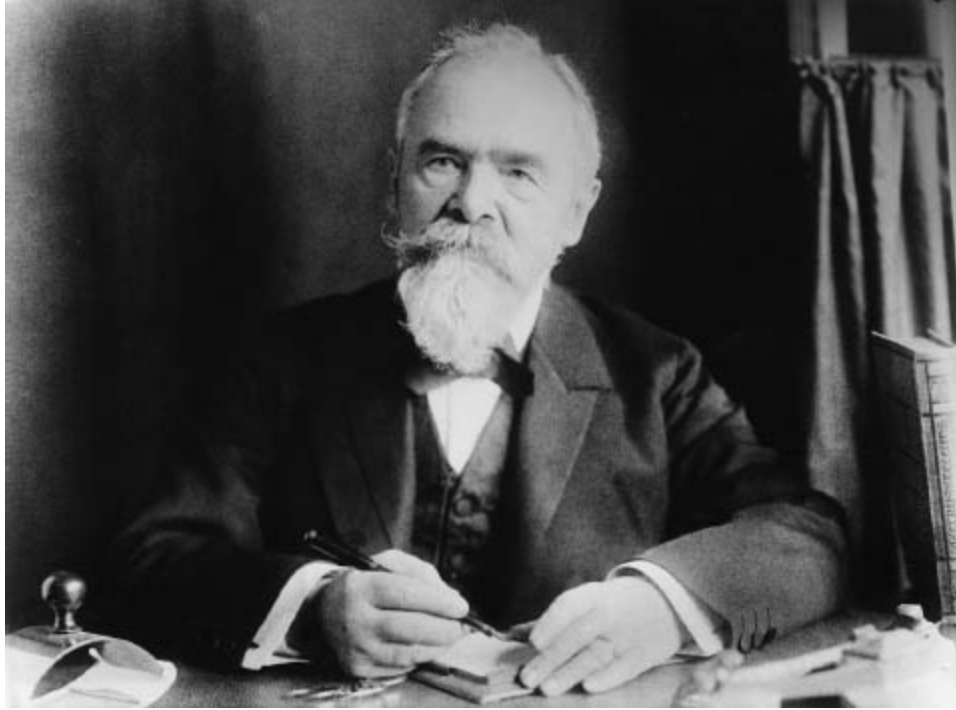
Here is intriguing material for a psychoanalyst or a forensic accountant—and it is far from the only matter in Diesel’s life and a career as an inventor and businessman that is puzzling and contradictory. No less intriguing is what we do not know about the origins of Diesel’s invention. We seem to know almost everything about Diesel’s quest for a new rational engine, and yet we cannot answer critical questions about the extent and the depth of Diesel’s awareness of previous similar engine designs. Was he really entirely ignorant of some of them, as he claimed to be?

Because most of the substantial writings by and about Diesel are available only in German, it is worth revisiting here at least the major goals, accomplishments, and failures of Diesel’s life based on those sources.

Diesel himself explained his intentions in considerable detail in 1893 in his first published book (Diesel 1893), in 1897 in a public lecture in Kassel (after building a series of prototype engines and submitting them to exhaustive trials) (Diesel 1897), and once more in 1913 (largely in response to unceasing criticism) in a detailed account of the engine's history and development process that was based on his meticulously kept workshop journals and other materials that describe all advances, setbacks, and eventual achievements (Diesel 1913). Diesel's contemporaries reviewed and criticized his work, subjecting it to detailed examination (Lüders 1913; Riedler 1914).

Diesel's accomplishments were later analyzed and appraised in greater detail by a study that took advantage of Diesel's collected papers (at the Deutsches Museum) and of records kept by Maschinenfabrik Augsburg (which merged with Maschinenfabrik Nürnberg, was renamed Maschinenfabrik Augsburg-Nürnberg in 1908, used the acronym MAN until 1986, and is now part of the MAN group and is known as MAN Diesel) (Thomas 1987). Other books dealing specifically with the history of Diesel engines are those of Cummins (1993) and Reuss (1993), and a unique account of Diesel's life and work was published by his son (Diesel 1937). An excellent overview of all aspects of the engine's origins and development was published by the MAN Diesel division as a 203-page catalog of the Augsburg exhibition commemorating Diesel's 150th birthday (MAN Diesel 2008a). Technical reviews of the machine's invention, development, and commercial acceptance are available in histories of internal-combustion engines by Sass (1962), Bryant (1976), and Sittauer (1978).

Diesel's father, Theodor, emigrated from Augsburg to Paris in 1850, where he owned a small workshop for manufacturing leather goods. Rudolf Christian Karl Diesel was born on March 18, 1858, in Paris. He was a bright and trilingual youngster (the family spoke German and French, and before her marriage his mother worked as a governess in London) who was very young when he began to be beset by headaches. His parents were not enthusiastic about his choice of profession before he enrolled at the Technische Hochschule in Munich in 1876. In January 1880, he graduated with the highest grades in the school's history, and his former professor, Carl von Linde (1842–1934; [fig. 3.4](#)), gave him his first job.



**Figure 3.4**

Carl von Linde, the inventor of artificial cooling systems, founder of Linde AG, and Diesel's first employer.

Photograph courtesy of Linde AG.

In 1879, one year after his lectures inspired Diesel to invent a superior internal-combustion engine, Linde set up Gesellschaft für Linde's Eismaschinen in Wiesbaden and launched a systematic effort to improve the existing methods of refrigeration. Eventually, the company's principal results were patents for the liquefaction of gases (in 1895) and for the separation of principal gases from the liquefied air (in 1902). Two months after his graduation, Diesel was employed by Linde to become his representative in France and its colonies, and in 1881 he was made director of a newly established ice-making company in Paris.

Starting in 1884, he devoted a great deal of time to the development of an engine that was powered by ammonia vapor and had high hopes for exhibiting it at the Universal Exposition in Paris in 1889, but he abandoned this project, much as he did a previous attempt to produce clear ice in bottles.

Before the end of 1899, Diesel left Paris to act as Linde's Berlin representative, and between 1890 and 1892 he produced the theoretical foundation for his new rational engine. This may be an apposite place to

explain Diesel's motives for developing a new engine. We know that personal satisfaction (by distinguishing himself as an eminent inventor), social acceptance, and the prospect of enrichment played major roles in Diesel's quest.

But Diesel was motivated by yet another impulse, one that cannot be dismissed as superficial. Since the early 1880s, he had a serious interest in social problems (in 1880, he wrote to his parents from Paris that "the workers' question is one close to my heart") and searched, ever a rational engineer, for what he believed to be the best solution to the problems of poverty. He read the works of French utopian socialists, argued for new socioeconomic arrangements (people's banks, cooperative factories), and hoped that his new engine would help small businesses stay competitive and promote industrial decentralization.

Just after patenting his theoretical design, he spelled out his ambitions for a small, inexpensive, and light engine (no larger than a sewing machine and able to work without water or electricity) explicitly in his programmatic book (Diesel 1893, 89):

It is undoubtedly better to decentralize small industry as much as possible and to try to get it established in the surroundings of the city, even in the countryside, instead of centralizing it in large cities, where it is crowded together without air, light, or space. This goal can be achieved only by an independent machine, the one proposed here, which is easy to service. Undoubtedly, the new engine can provide a sounder basis for the development of small industry than recent trends, which are false on economic, political, humanitarian, and hygienic grounds.

This reasoning was based on the premise that only large factories were able to invest in large efficient steam engines, and it was stimulated by theories of industrial decentralization that were widely advocated during the two closing decades of the nineteenth century. Diesel's list of potential users for his small engines included watchmakers, dental technicians, and machinists (small lathes operators), and he envisaged possible uses ranging from sewing, ironing, and vegetable chopping to hackney cabs, velocipedes, and invalid chairs. In his 1897 speech to the Verein Deutscher Ingenieure in Kassel he again noted the engine's potential role in fostering industrial decentralization. In retrospect, it is remarkable how completely these forecasts failed. None of the uses envisaged by Diesel for his small engine became a reality. Indeed, the mere notion of a diesel-powered sewing machine or a wheelchair would be soon seen as ridiculous. Moreover, subsequent development of diesel engines led to steadily more powerful machines quite unsuitable for any small-scale uses.

Diesel's social concerns got their most systematic expression in *Solidarismus: Natürliche wirtschaftliche Erlösung des Menschen* (Diesel 1903). This book is clearly beholden to various thinkers about workers' empowerment active during that era. Diesel extolled workers' voluntary actions, above all worker-run factories that would ensure a comprehensive social net, and in his infatuation with a supposedly perfectly engineered social organization, he called workers' cooperative *beehives* and the workers themselves *bees* with identification cards and contracts.

Ten thousand copies of the book were printed and were priced cheaply, but only three hundred were sold. There would not be the great social upheaval that Diesel had hoped for. Even so, after the book's publication, Diesel remarked that while his invention of a new engine is "well and good," his "chief accomplishment is that I have solved the social question" (Diesel 1937, 395). Diesel's belief that his engines were one of the most important means to the solution of the social question was completely wrong. A mere notion of a diesel-powered sewing machine or a wheelchair would soon be ridiculous: within years of their introduction (during the late 1880s) small electric motors claimed, rapidly and conveniently, these, and many other, niches.

These machines, patented by Nikola Tesla (fig. 3.5) in 1888 and then rapidly adopted for a growing variety of tasks, had a number of advantages compared to any combustion engine, external or internal—no need for fuel (and hence no stoking or refueling), quiet and clean operation, very high conversion efficiency of electrical energy to mechanical power, easy startup, simple, convenient control of units dedicated to individual tasks, and above all, no problems in making them in any capacity (including tiny devices that were suitable for such precision work as watch making, medium-size devices that could reliably run many metal-working machines in small workshops, and large industrial units).

Consequently, Diesel's intent to turn the tide of industrial centralization by using his new rational engine as the prime mover of small-scale decentralized manufacturing was a misplaced ambition from the start, and the ascent of electric motors turned it into a complete failure. A century later, it could be argued that the eventual outcome was not completely one-sided. Diesel's engines have never powered any return to decentralized manufacturing, but many small- or midsize stationary Diesel engines have been of enormous help in mechanized farming and large numbers of

relatively low-capacity engines are now used to generate electricity in places that have no connection to transmission lines. On the other hand, the massive diesels that are used in modern shipping have helped to create the very opposite of Diesel's vision—an unprecedented concentration of specialized manufacturing in just a handful of locales (now particularly in China) and a subsequent worldwide distribution that takes advantage of inexpensive, diesel-powered shipping.



**Figure 3.5**

Nikola Tesla, the inventor of the induction electric motor—an efficient, reliable, and flexible energy convertor whose ubiquitous use revolutionized industrial production.

Photograph courtesy of the Tesla Society.

The key ingredient of Diesel's theoretical solution to the challenge of designing a machine that closely replicated Carnot's cycle called for admitting approximately nine times more air into the cylinder than was needed for fuel combustion and then compressing it to such an extent that ignition temperature would take place only due to compression. At that point, fuel would be injected and ignited, but the ensuing rise in temperature due to combustion would be nearly equal to the cooling of the expanding air, resulting in constant temperature (isothermal) combustion

and obviating any need for external cylinder cooling (just the opposite, as insulation would be required).

None of the key elements of Diesel's proposal was revolutionary in itself. The gasoline engines that were invented by Benz, Daimler, and Maybach and installed in the first generation of passenger cars used compressed air (albeit to low levels) as a working medium. Carnot himself proposed using compression ignition, and as Diesel was eager to stress, it would be incorrect and superficial to claim that the self-ignition of the fuel is the most important attribute of his process. As he put it, it would be absurd to build a much heavier engine merely for the sake of ignition when the machine is cold because once the engine is warmed up self-ignition takes place at lower pressures. But the engine's principal goal was the highest practical efficiency, and this necessitated the use of compressed air (Diesel 1913). Thermodynamics made it clear a long time ago that higher pressures will lead to higher efficiencies.

Moreover, Diesel could not have been entirely unaware of the writings and proposals for similar machines that preceded his own efforts, above all the published work of Otto Köhler (1887) and Franz Grashof (1890), and of the patent for *Improvements in Engines Operated by the Explosion of Mixtures of Combustible Vapor or Gas and Air* filed in 1890 by Herbert Akroyd-Stuart and Charles Richard Binney on behalf of Richard Hornsby and Sons. This engine, which was commercially available by 1892, used pressurized fuel injection, but because of its low compression (620 kPa versus more than 3 MPa for Diesel's early engines), ignition could not take place in the combustion chamber, and the engine needed a separate vaporizer (known as a hot bulb) attached to the cylinder head (Robinson 1931).

Yet Diesel claimed (with some corroboration from some of his coworkers and supporters) that he was unaware of those developments, and he kept pointing out that there was no precedent for the totality of his proposal that combined excess air intake, high compression, and compression ignition and that eventually resulted in a machine of unprecedented efficiency. That is certainly true when his successful design of 1897 is compared with the Akroyd-Hornsby engine of 1892, which was no more than 12 percent efficient, offering essentially no improvement in comparison with the best existing compound steam engines. But these are secondary matters. The principal problem with Diesel's idea was that he failed to realize that to



compress so much air to such a high level and temperature (his initial specifications called for pressures of as much as 250 atmospheres—that is, 25.3MPa and temperatures between 800 and 1,000°C) could not be done with such a relatively small volume of fuel. Simply put, the engine could not run under its own power.

But in early 1892, Diesel reaffirmed his vision and submitted his patent on February 26. After two rejections (most important, the Patent Office argued that the submission did not show how the idea could be made to work in a real engine) and necessary rewrites, he was granted the German rights for the machine (Reichspatent 67,207, *Arbeitsverfahren und Ausführungsart für Verbrennungskraftmaschinen*) on December 23, 1892 (fig. 3.6). The patent was for a

working process for an internal-combustion engine characterized by the fact that . . . pure air . . . is so highly compressed by the piston that the resulting temperature is far above the ignition temperature of the fuel . . . and addition of fuel . . . occurs so gradually that combustion takes place without essential pressure or temperature increase because of the outward moving piston and the expansion of compressed air.



Diesel's Patent Number 67207, February 1893.  
(M.A.N. Werkarchiv)

**Figure 3.6**

The front page of Diesel's 1893 patent for *Arbeitsverfahren und Ausführungsart für Verbrennungskraftmaschinen*.

Photograph from the MAN Bildarchiv.

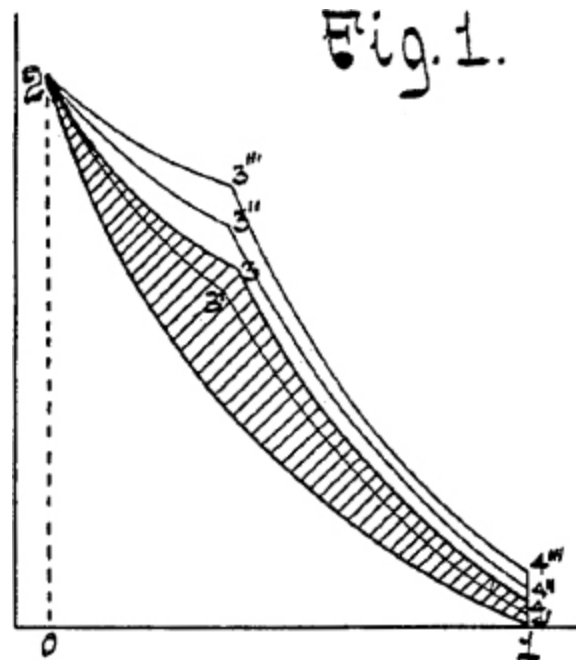
Diesel thus secured a patent whose main claim (isothermal expansion) could not be embodied in a working engine. That he did not realize this is easy to explain given his lack of experience in any previous engine design that would actually lead to a working machine, his excessive self-confidence, his uncritical appraisal of an idea that he saw as an embodiment of engineering perfection, and his eagerness to reap accolades and commercial success. What is much harder to explain is that in its final form the claim virtually followed the wording that was suggested by the Patent Office after its initial misgivings, and what is most inexplicable is that some very experienced thermodynamicists and accomplished engine designers were as unaware of that basic flaw as was Diesel himself.

By definition, an engine that replicated Carnot's cycle would have to work with isothermal expansion. This means that after adiabatic compression of the air, the fuel would have to be introduced at such a rate that the heat of combustion would replace only the heat lost due to gas expansion. Indeed, Diesel's patent application shows a theoretical diagram with a clearly isothermal curve for the fuel injection and combustion segment of the cycle (fig. 3.7). As a result, all thermal energy would be converted to mechanical energy, and the temperature inside the cylinder would be maintained at the maximum achieved during the compression stroke.

But Diesel remained confident that the higher temperature differential of a working medium would yield efficiencies that were superior to those of a steam engine. Moreover, after his previous experience with superheated ammonia vapor, he also favored the use of high pressure because only through a high-pressure differential during expansion is it possible to use effectively a large temperature difference—but with air both as his working medium as well as a medium for combustion. Comments from Linde and from Moritz Schröter (1851–1925), another of Diesel's former professors at the Munich Technische Hochschule, led Diesel to modify his theoretical design by giving up the idea of isothermal compression but he still clung to the idea of isothermal expansion. This modified plan appeared in Diesel's programmatic book that was published in January 1893 by Springer (Diesel 1893) and it received generally a very positive, even enthusiastic reception.

Before obtaining his patent, Diesel pursued his contacts in German industry to secure the necessary financial and material backing for transforming his theoretical construct into a practical working machine.

Eugen Langen at Deutz turned him down, and although Linde refused to get personally involved, he was helpful during Diesel's negotiation with Heinrich von Buz (1833–1918), general director of the Maschinenfabrik Augsburg, at that time Germany's leading mechanical engineering enterprise (fig. 3.8).



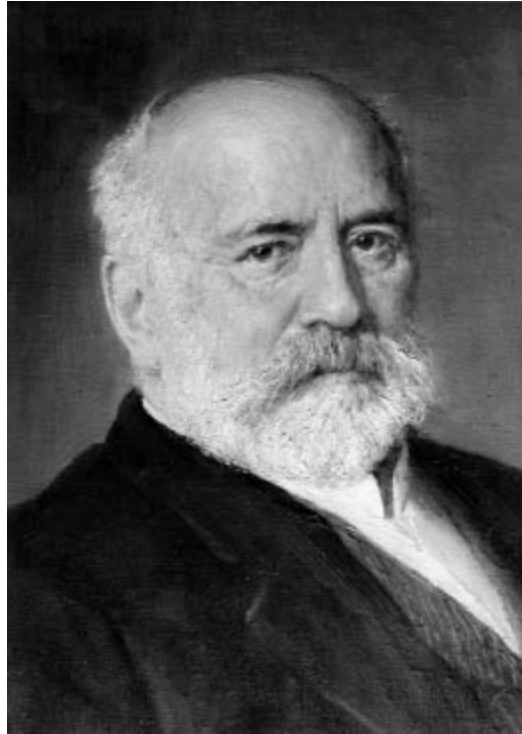
**Figure 3.7**

Figure 1 in Diesel's patent application, showing a theoretical indicator diagram of his engine where "the curve 2-3 corresponds to the period of admission and consumption of fuel."

Reproduced from Diesel's U.S. patent application of July 15, 1895 (available from the U.S. Patent and Trademark Office).

At first, Buz thought that the entire development scheme was too risky, but he changed his mind after Diesel's new specification called for the pressure of 44 atmospheres rather than the originally intended 150 to 250 atmospheres (no manufacturer could have handled the latter pressures in the 1890s). On February 21, 1893, Diesel signed an agreement that gave the company the marketing rights for the machine in parts of Germany in exchange for agreeing to build the first experimental engine, according to Diesel's plans, within six months. On April 10, 1893, Diesel signed a similar agreement with Friedrich Alfred Krupp (1854–1902) of Essen, who also agreed to pay Diesel an annual salary of 30,000 marks during the testing period and a royalty of 37.5 percent for every engine sold, which

were extremely generous conditions by any measure. Two weeks later, the two companies agreed to share the developmental cost of the new engine and to conduct all experimental work in one laboratory, where Diesel would be in charge until a marketable machine was developed.



**Figure 3.8**

Heinrich von Buz, general director of Maschinenfabrik Augsburg, was the most important supporter of Diesel's efforts to convert an idea into a commercial machine.

Photograph from the MAN Bildarchiv.

During the summer of 1893, Diesel made modifications that represented major departures from the patented proposal: he had abandoned the idea of isothermal combustion and concluded that combustion at constant pressure is the only choice. Compression was to reach no more than 30 to 40 atmospheres, the engine was to be water-cooled, and operating speeds were to be as fast as possible. In November 1893, Diesel applied for his second German patent (Reichspatent 82,168, granted in July 1895) dealing with the working process and its method of execution for a practical engine. But in retrospect, it is clear that Diesel's idea would not have been translated into a practical machine in such a relatively short period time without the interest and commitment of Heinrich von Buz and Friedrich Alfred Krupp. The two

men and their companies showed a great deal of foresight, perseverance, and loyalty and spent a considerable sum of money because turning Diesel's theoretical concept of a rational engine into a commercially appealing product proved to be a much harder and longer task than the inventor had originally anticipated.

### **From Invention to a Marketable Machine**

The process of transforming Diesel's original patented proposal to a working internal-combustion engine can be perhaps best characterized as a successful failure. The failure part was a foregone conclusion as Diesel ignored key observations that Carnot himself emphasized—that in practice we should never expect to utilize all the motive power of a fuel and that an ideal engine cycle is a hypothetical construct that cannot ever be translated into a working machine. Even after expert criticism and his own calculations led him to conclude that isothermal combustion was beyond practical reach and that combustion under constant pressure was the only solution, enormous difficulties were still ahead (Diesel 1893).

The first test engine, which was built according to Diesel's plans between March and July 1893, had a cylinder diameter of 150 mm and stroke of 400 mm (fig. 3.9). As is shown by a negligible area of the engine's indicator diagram (fig. 3.10a), it was never able to operate under its own power (it was driven by a transmission belt). A rebuilt engine with air-blast fuel injection (using Linde's compressor) was ready in January 1894, and the second test period lasted until April. On February 17, 1894, the engine ran for the first time freely, albeit for only a minute at 88 revolutions per minutes. Subsequently, the engine displayed irregular combustion diagrams with late ignition followed by explosions (see fig. 3.10b), but it also had some quiet runs at increased power (fig. 3.10c). The third testing period ran from May to October 1894 as the engine was burning gasoline and kerosene. The fourth period, between October and December 1894, was devoted to testing with gases, and although it yielded some encouraging work diagrams, the overall performance was so poor that Diesel considered giving up the key idea of compression ignition to make the machine run.

This lack of progress led to the decision to build an entirely new engine that was ready by March 1895. Its piston had a larger diameter (200 mm), its combustion chamber was in the cylinder head, and it had a better fuel

distributor. With this machine, Diesel was finally on the verge of a successful design. On May 1, 1895, two years after the beginning of his tests, he wrote in his experimental record: “It should be taken for certain that a right indicator diagram has now been reached” (Diesel 1913, 42–43; [fig. 3.10d](#)). By July 1895 the engine achieved mechanical efficiency of 67.2 percent and that pushed the net performance to just over 20 percent (Diesel 1913, 45, 47).

As indicated by a letter to his wife written on July 3, 1895 (cited in MAN Diesel 2008a, 43), Diesel was now finally satisfied and confident:

My engine is continuing to make great progress. I am now so far ahead of everything else that has been done to date that I can truly say I am leader of the whole pack both on this and the other side of the ocean in this first and most exclusive technical profession, engine building. . . . If I were that kind of person . . . , I would be proud. But I am quietly content, without making a song and a dance, satisfied in the knowledge that I have completed a useful piece of work and pleased that our future is secure, as it now is.

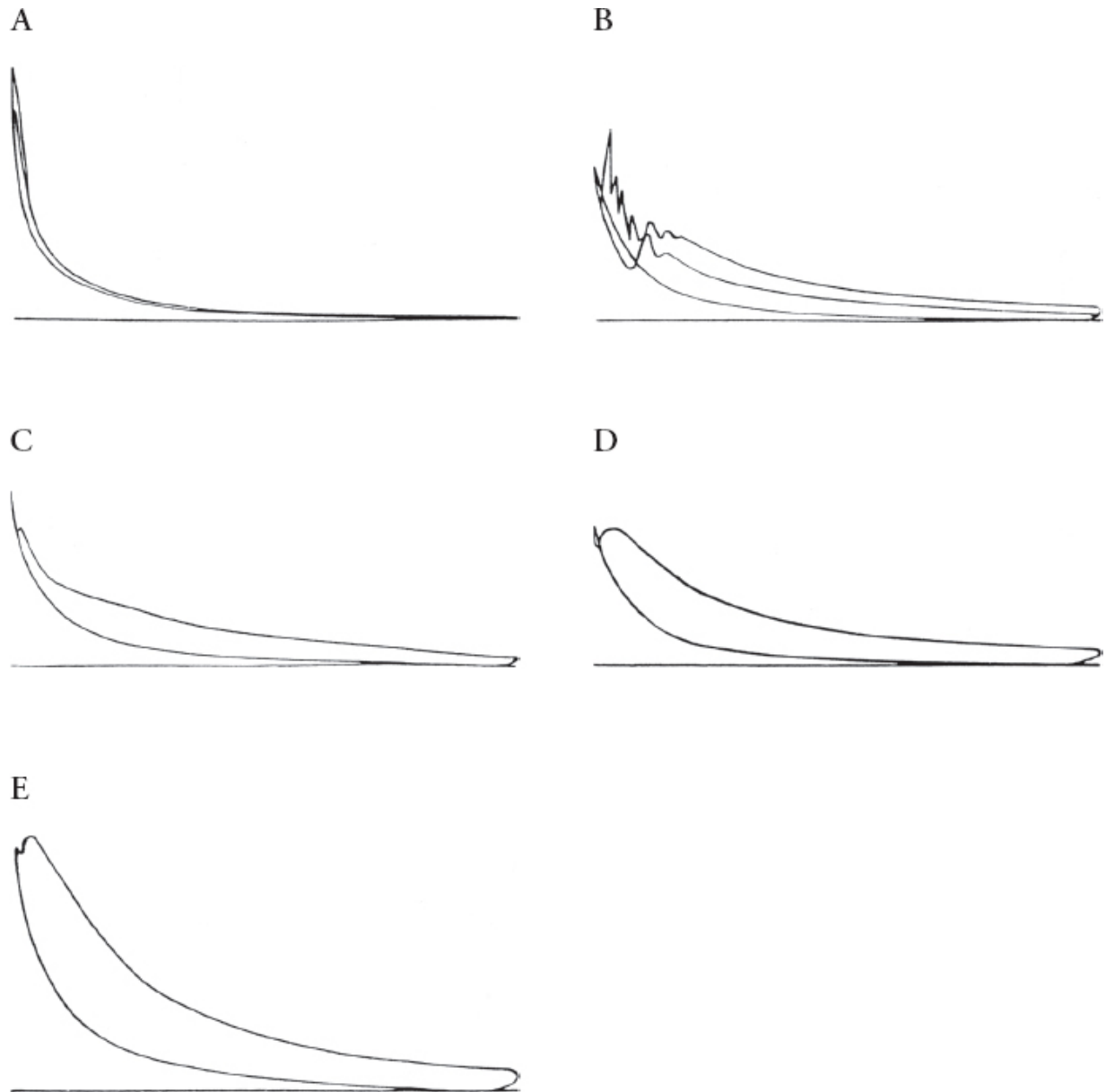


**Figure 3.9**

Diesel's first engine, used in experiments between 1893 and 1895 and now in the MAN Museum in Augsburg.

Photograph from the MAN Bildarchiv.





**Figure 3.10**

Indicator diagrams mark the stages in the development of Diesel's experimental engines: (a) spring 1893, no net power; (b) early 1894, irregular performance; (c) early 1894, a quiet, low-power run; (d) May 1895, finally, a "right indicator diagram"; (e) February 1897, a diagram from the finished engine prototype (diagrams were selected and are reproduced from an appendix in Diesel 1913).

In July, the company also set up a design bureau for the full exploitation of the engine's commercial potential. Unrealistic expectations thus began even before the engine's tests were completed. A formal decision to recommend serial production was made by Diesel and the Augsburg plant to Krupp in January 1896, justified by the fact that the tested machine was

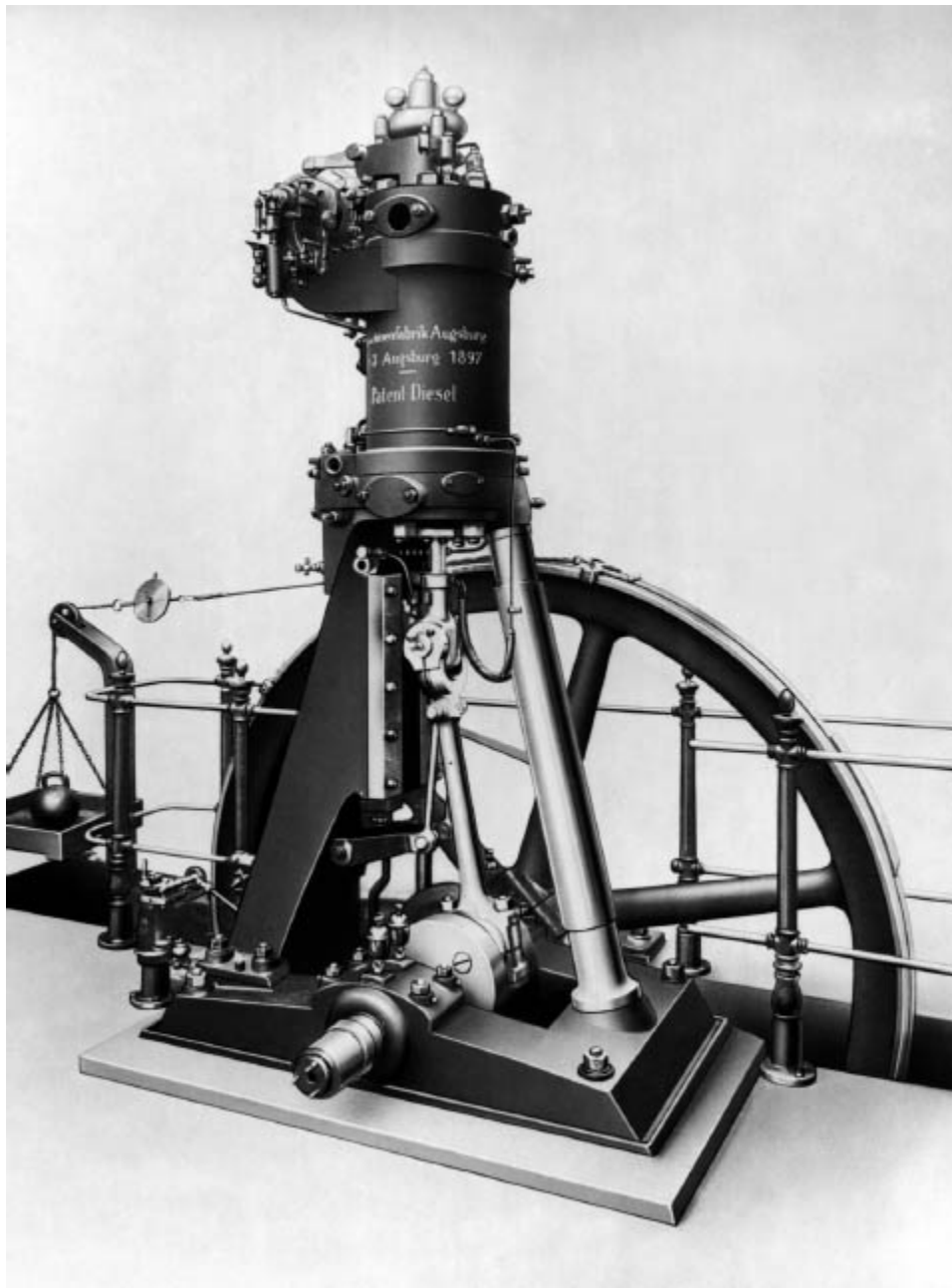
significantly superior to any other liquid-fuel engine. But in February 1896 a decision was made to build a third, somewhat larger prototype with a piston diameter of 250 mm, a stroke of 400 mm, a single-stage air compressor, and a sieve vaporizer in the fuel nozzle. This machine was used to perform the last, sixth series of test. It began to work in December 1896, and next month it reached thermal efficiency of almost 32 percent and mechanical efficiency of nearly 76 percent for a net efficiency of just over 24 percent.

On February 17, 1897, Moritz Schröter performed the official test with the following results at full power of 13.5 kW (17.8 hp) at 154 rpm—thermal efficiency 34.7 percent, mechanical efficiency 75.5 percent, net efficiency 26.2 percent (Diesel 1913, 84), and a maximum pressure of 34 atmospheres (3.44 MPa, an order of magnitude below Diesel’s initial maximum specification). One of its indicator diagrams is shown in [fig. 3.10e](#). As the engine weighed nearly 4.5 t, it had a high mass-to-power ratio of 333 g/W. This third test machine is now displayed in the Deutsches Museum, where it is identified as the first functional Diesel engine ([fig. 3.11](#)). In a later test in the same year reached the net efficiency of 30.2 percent.

In contrast, the typical efficiencies of commonly deployed Otto engines at that time were between 14 and 17 percent. Diesel’s original goal of a Carnot-like rational engine remained elusive, but he still had a machine whose efficiency was twice as high as that of any other combustion device, and he could be very optimistic about its engine’s commercial future. Even sixteen years later, after all the problems and setbacks that the engine had been through, he maintained that by 1897 “with that [i.e., the performance test], the task of the inventor was done” (Diesel 1913, 78), and he called his invention *eine durchaus markthäftige Maschine* (a thoroughly marketable machine).

Diesel recognized the debt he owed to Buz, and it would not be an exaggeration to conclude that if any other name is to be permanently associated with the development of diesel engine, it must be that of Heinrich von Buz (see [figs. 3.8](#) and [3.11](#)). But both men were mistaken in their belief that commercialization of the machine was at hand, and both paid a price for this premature conclusion. Diesel went as far in a letter (now in the MAN archive) to his wife as saying that difficulties were over and that “the rest will develop automatically on its own worth” (cited in

Thomas 1987, 152). This miscalculation has become a favorite example for historians to illustrate the demands, delays, and frustrations that beset the process of commercialization of any new technique. As difficult as the road from a concept to a working prototype may be, it might be even more difficult to establish a serial production of reliable machines whose efficient performance becomes the best means to conquer new markets.



**Figure 3.11**  
Diesel's third experimental machine, used in 1897 to run the official tests.

Photograph from the MAN Bildarchiv.

On June 16, Diesel and his former professor Moritz Schröter unveiled the details of the engine's construction and performance in talks to the Verein Deutscher Ingenieure in Kassel. Diesel stressed its net thermal efficiency and Schröter confirmed that the engine was now "completely marketable and completely worked out in all details." That was, as his son Eugen wrote forty years later, *der Höhepunkt in Diesels Laufbahn* (the high point of Diesel's life journey) (Diesel 1937, 268). And we have a captivating memento of that moment—an elegantly dressed Diesel with a top hat and umbrella linking arms with von Buz, the magisterial doyen of the German machine industry, and with a smiling Schröter (fig. 3.12).

One important task remained to be completed before the machine was put into serial production—the choice of the best fuel. Although many kinds of gaseous and liquid fuels were tested during the six series of Augsburg trials, Diesel's principal goal was always to run the engines on a suitable liquid fuel.

Systematic tests with liquids (including different crude oils from the United States, Russia, Galicia, Romania, and Asia) began before the end of 1897, only after a final working prototype became available. Kerosene served as the standard for comparisons, and the fuel that soon became the dominant energizer of diesel engine—gas oil received from the United States—was tested in December 1897 and found immediately superior to kerosene. Meanwhile, Diesel did not lose any time in converting the new engine's considerable industrial promise into a great personal fortune. Besides the initial 1893 agreements with von Buz and Friedrich Alfred Krupp, he also gave exclusive use of his patent in Switzerland, with the option of future engine production, to Sulzer Brothers of Winterthur, the country's leading engine maker.

In 1897, he signed production contracts with the Augsburg factory (for Germany) and with Friedrich Alfred Krupp (for Austria and Hungary), both stipulating 5 percent royalties and an annual advance of 30,000 marks for the first five years, and with three other German firms (including Deutz). Even more rewarding were his sales of patent rights abroad—to Frédéric Dyckhoff in France (for 600,000 francs; exclusive patent rights were ceded already in 1894 and Société Française des Moteurs R. Diesel was set up in 1897); to Mirrlees, Watson Yaryan in Glasgow (for 100,000 marks); to

Markus Wallenberg in Sweden (Aktiebolaget Diesels Motorer for 50,000 kronor); and to Emanuel Nobel's Branobel in Russia (for 600,000 marks in cash and 200,000 marks in stock). Agreements reached in 1898 also included Burmeister & Wain in Copenhagen (later a pioneer of marine diesel propulsion) and several smaller German companies.



**Figure 3.12**

Rudolf Diesel, Heinrich von Buz, and Moritz Schröter photographed at the Verein Deutscher Ingenieure meeting in Kassel on June 16, 1897, where Diesel and Schröter revealed the design and unprecedented performance of a new rational engine.

Photograph from the MAN Bildarchiv.

But the greatest reward came from licensing the engine to Adolphus Busch (1839–1914), cofounder of Anheuser-Busch, for the manufacturing in the United States by the Dieselmotor Company of America (for 1 million marks and 6 percent royalties). Diesel also got involved in setting up a new company that was explicitly devoted to making the machines:

Dieselmotorenfabrik AG Augsburg was registered on January 1, 1898, and began to ship the first engines in 1899. But during the triumphal years of 1897 and 1898, Diesel also had to deal with two major patent challenges. The first one, by Otto Köhler (at that time working for Deutz), was seen as a serious matter. After all, in 1886, the company had successfully challenged the rights of Otto's patent of four-stroke engine for Germany.

But the challenge had never gone public. By August 1897, it was settled by Krupp, who offered Köhler an annual payment of 3,000 marks in return for dropping all claims. The second challenge—filed on July 31, 1897, by Emil Capitaine—was more serious. Capitaine, a Frankfurt engineer and inventor who had previously patented engines working at 16 atmospheres with a heated vaporizer ignition (perhaps best described as halfway between standard gasoline engines and Diesel's machines), asked a court for an annulment of Diesel's patent. But Capitaine's claim was rejected nearly nine months after its submission (on April, 21 1898), and he settled on July 12, 1898, for the payment of 20,000 marks.

Looking back at that stressful period and at production setbacks that were to follow, Diesel (1913, 152) concluded that “the introduction [of an invention] is a time fraught with combating stupidity and jealousy, inertia and venom, furtive resistance and an open conflict of interests, an appalling time spent battling with people, a martyrdom to be overcome, even if the invention is a success.” These months of unceasing stress brought a serious deterioration of Diesel's mental health: in October 1898 he checked himself into Neuwittelsbach sanitarium near Munich, and in late January his doctors sent him to Merano where he stayed until the end of March 1899 (he had another relapse in 1901–1902).

Meanwhile, the makers of Diesel's machines found it difficult or impossible to produce reliably working units. Problems caused by high pressures (and hence high temperatures) that were unprecedented in internal-combustion engines cascaded through the machines, stressing,

overheating, rupturing, and wearing out their parts. In addition, single-stage air compressors were prone to ignite the lubricating oil or to explode, the sieve vaporizer kept failing to deliver the fuel, and the use of nonstandardized liquid fuels resulted in unpredictable (and often poor) engine performance. Diesel was desperate as he complained to Ludwig Noé, a young engineer who got one new machine running, “No machine works! Everything around is breaking down!” (Diesel 1937, 342). But such interventions came too late to prevent large declines in the value of the companies that were making diesels.

The first machine sold by the Augsburg plant in November 1897—a 60- to 70-horsepower engine for a matchmaking factory owned by von Buz’s brother in Kempten—began to work in April 1898, but it required constant supervision by an experienced mechanic for a year before it could run unattended (but after the company changed owners, it powered electricity generators until 1939). The quality of engines made by other manufacturers was much worse. Nürnberg Engine Works stopped its engine production in 1898 as did Krupp AG (it began making the engines two decades later), and the Diesel Engine Company quit in 1900. Manufacturers simply did not have materials that were able to cope with high pressures and maintain requisite tight seals or ready-to-use devices capable of reliably injecting precise amounts of fuel into pressurized chambers at exact intervals. Ironically, while many newly sold Diesel engines were more in repair than in operation, a diesel engine exhibited at the Exposition Universelle in Paris got a Grand Prix.

All of these manufacturing and licensing setbacks damaged the reputation of the General Society, and its stock valuation suffered accordingly. Through all of this, only the Augsburg plant (MAN) and Nobel Engine Works in St. Petersburg persevered in developing a reliable, serial product. Progress was slow. By the end of 1901, fewer than three hundred Diesel engines with a total capacity of less than 7.5 MW (about 26 kW or 35 hp per engine) were sold in Germany and abroad, while at that time the German capacity of other industrial internal combustion machines was on the order of 50 MW. Diesel had no personal involvement in these gradual, cumulative improvements that eventually reversed the tide of bad news and failed performance and made the engine the dominant or the sole prime mover of entire industrial sectors.

One could thus accurately speak of four fundamental phases in developing the engine. In Diesel's phase, the idea was formulated and patented and von Buz and Krupp were persuaded to finance its development (1880–1892). In the Diesel and Maschinenfabrik Augsburg phase (1892–1897), the construction of three test engines resulted in a working prototype that was by no means ready for licensed serial production. In the Maschinenfabrik Augsburg phase (1897–1907), the factory was the principal maker of engines and a developer of reliable designs. And in the everybody-joins-in phase after 1907 and 1908, Diesel's 1892 and 1893 patents expired, and manufacturers in Europe and North America began producing growing numbers of engines for various stationary uses and for water transport.

Diesel had very little to do with this progress. In 1903, he participated in tests of the first diesel-powered river boat (the *Petit Pierre*, which was to work on the Rhine-Marne canal), built by his old friend Frédéric Dyckhoff, and later he had some contacts with Sulzer company in Switzerland when it was designing and building the first diesel-powered mainline locomotive. In November 1912, he gave a major lecture to the Schiffbautechnische Gesellschaft (Society of Naval Architects) at the Technische Hochschule in Berlin in which he detailed his progress in testing the three engine prototypes between 1893 and 1897. After its conclusion, he was criticized and personally attacked by Alois Riedler (an Austrian professor of mechanical engineering, since 1888 at the Berlin Technische Hochschule) and by Adolf Nägel. They accused him of not giving credit to previous designers of engines with similar features; developing a machine that was merely working (*gangbar*) but not really useful (*brauchbar*) and by no means market-ready (*markthäftig*); not acknowledging Maschinenfabrik Augsburg for accomplishing the last two critical steps; and enriching only himself.

In his defense, Diesel noted that the lecture dealt only with the period of 1893 to 1897 and that in 1897 it was not only he but also von Buz and Krupp who became convinced that the engine was ready for serial production. In 1913, Diesel expanded the lecture and added a brief summary of post-1897 developments. It became his last published work. As already noted, just a few weeks later, he was not found in his cabin on a ferry that was carrying him to England for an opening ceremony for a new Diesel engine factory. Controversies regarding his invention continued after



his death. In October 1913, Johannes Lüdgers, a seventy-eight-year-old former professor at the Technische Hochschule in Aachen, published a lengthy book (236 pages) that mounted a sustained and repetitive (and hence tedious) critique of Diesel's expertise and ideas and also a highly personal attack on nearly everything that Diesel had done.

The book was finished before Diesel's death, but Lüdgers (1913, 236) added a postscript whose closing admonition exemplifies its tone: "Regardless how Diesel may be now judged, . . . if one wants to write his obituary, that task must be thought of as a matter of history, and before such a forum the phrase *de mortuis [sic] nil nisi bene* does not count." (The full correct Latin quotation is *de mortuis nil nisi bonum dicendum est*—nothing must be said about the dead except the good.) The next year came Riedler's (1914) critical volume, but by that time, these attacks notwithstanding, the post-1898 reversals and disputes about the originality of Diesel's design and about the disparity between his patent and the working machine were already mostly a matter of historic interest.

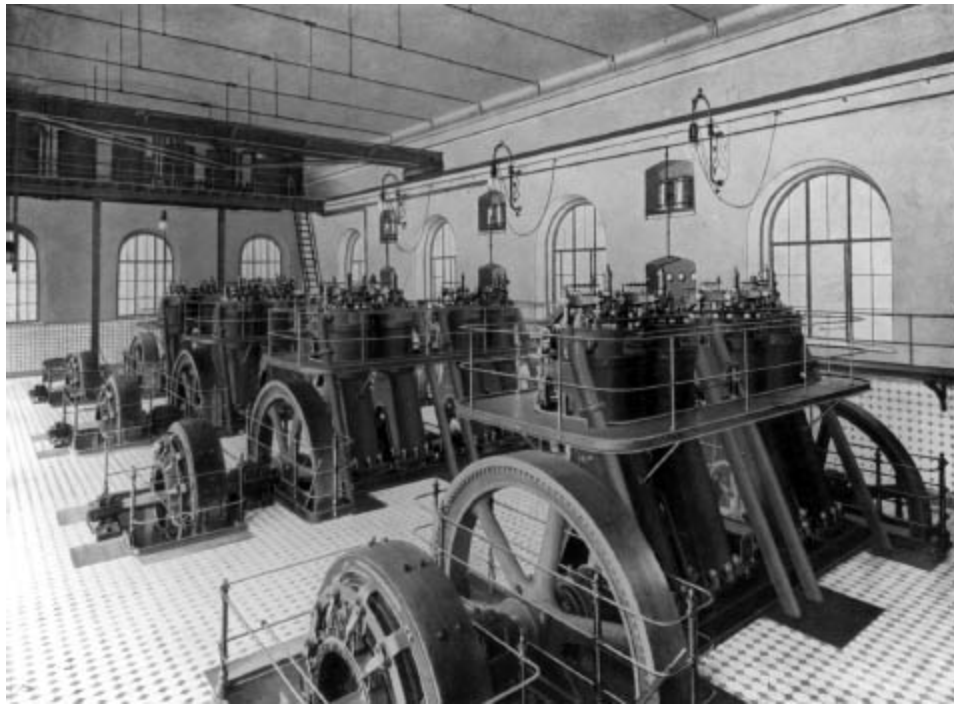
We will never know how much all of this contributed to Diesel's decision to end his life. By 1913, Diesel was in a perilous mental state, hiding his bankruptcy from his family even as his engines were finally and unmistakably ascendant, well on their way to become dominant prime movers in shipping and on railways. Moreover, it was not difficult to foresee their eventual adoption by land vehicles. In an obituary, Henry Suplee wrote in *Scientific American* that Diesel's engine, "the result of the union of theory and practice," was "the greatest advance in the generation of power from heat since the invention of the separate condenser by Watt" and that "the revolution which such machine is creating in the development of power must appear" (Suplee 1913, 306). And so it did—first on and under water and after World War I also on land.

## **The Diffusion of Diesel's Engines**

Scores of the first diesel engines that were sold between 1898 and 1902 in Europe and the United States were for relatively small to medium-size stationary industrial applications, and the Augsburg plant was the industry's leader (it produced 114 during that time). The two men who were responsible for the early advances of the company's diesel engine design were Imanuel Lauster (1873–1948), who worked with Diesel on the design

of the third experimental engine, and Hugo Güldner (1866–1926), who was hired in 1899 as chief engineer and lead designer and who developed the first two-stroke engine. Between 1898 and 1900, Lauster also designed the first practical crosshead engine and then, until his retirement in 1934, participated in many new designs. Sulzer also sold its first engine, a four-stroke machine rated at 14.7 kW, in 1898.

All of the engines that were sold during the first five years of often troublesome production were relatively small stationary machines. The first diesel-powered electricity generating plant was a clear capacity step-up for stationary diesels. When it began operating in Kiev in 1904 (to generate electricity for the city's tramways by burning crude oil), its four Augsburg-made four-stroke engines had a total capacity of nearly 1.2 MW at 160 rpm (fig. 3.13). Two challenges complicated the use of engines for ship propulsion—their high specific weight (and considerable bulk) and their nonreversible operation.



**Figure 3.13**

In 1904, the world's first diesel-powered electricity generating plant in Kiev had four diesel engines with total capacity of nearly 1.2 MW.

Photograph from the MAN Bildarchiv.

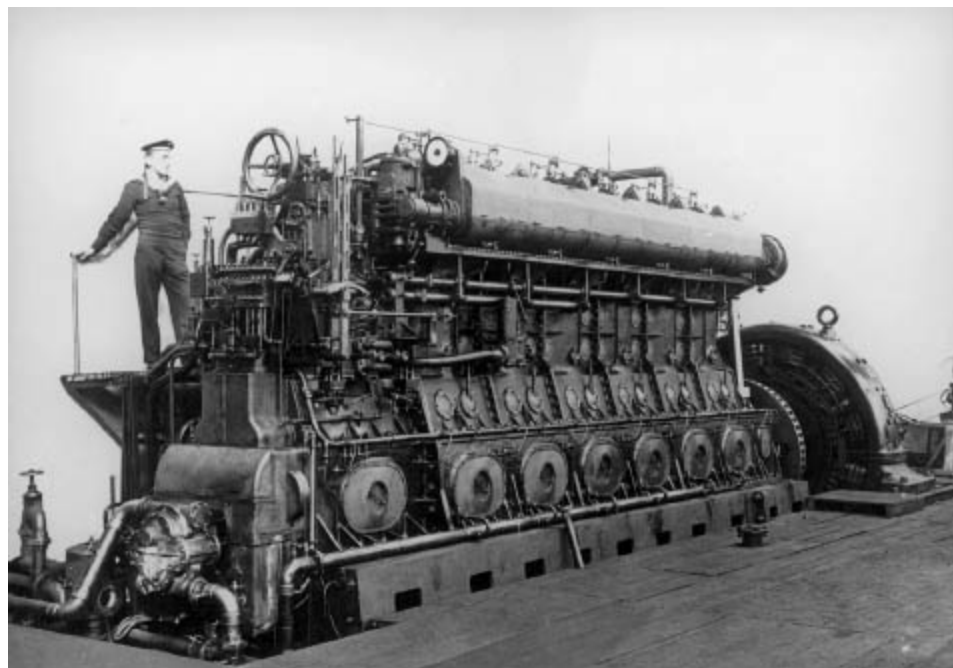
The first commercial diesel engine that was sold in 1898 had a mass-to-power ratio of 296 g/W (only about 11 percent lower than the engine that was certified in the 1897 trials), which was higher than that of the best contemporary steam engines (they rated less than 100 g/W) and an order of magnitude higher than that of the best automotive gasoline-fueled engines. The engine's lack of reversibility was a critical shortcoming for the maneuverability of diesel-powered vessels. Frédéric Dyckhoff (Diesel's friend and one of the earliest licensees of the new machine) built a direct reversing mechanism but abandoned it as impractical. Instead, in 1903, he used adjustable propeller blades in his canal boat *Petit Pierre*, which he equipped with a small (19 kW, 360 rpm), three-cylinder four-stroke engine built by his Société Française des Moteurs R. Diesel and Sautter, Harlé & Cie (Koehler and Oehlers 1998). The boat began to work on the Marne-Rhine canal in September 1903, and before the end of October, Dyckhoff invited Diesel to spend a day on the vessel.

Afterward, Diesel wrote to his eldest son that “this is the beginning of very great technical advance of which the world will speak a great deal in the future” (Diesel 1937, 377). As I show in detail in [chapter 5](#), he was absolutely correct on the first account but wrong on the second one. Diesel's engines, much like the other prime movers that power the modern civilization, do their work largely ignored and generally unappreciated. But *Petit Pierre* was not the first vessel that powered a diesel. That primacy belongs to the *Vandal*, a small (800 dwt, 75 m long) river tanker owned by the Nobel Petroleum Company and used on the Caspian Sea and on the Volga. Its first trip took place in the spring of 1903, and it was powered by three Swedish-made, three-cylinder engines that were rated at 89 kW. Desired maneuverability was achieved by making it the world's first diesel-electric vessel. The ship's three propellers were driven by electric motors that were powered by direct-current generators. Nobel's company launched a second river tanker in the summer of 1904. The *Sarmat* had two 135-kW engines, and it used a semi-electric drive that was designed by an Italian engineer, Cesido del Proposto (Koehler and Oehlers 1998).

An early marine application of diesels was on submarines because the machines offered considerably greater efficiency (and required less fuel to be carried onboard) and their heavier fuel was much less volatile than gasoline. The Augsburg plant began to develop a submarine design in 1901, but the French navy was the first organization to install a four-cylinder 150-

kW engine (made by Sautter, Harlé) on the *Aigrette* in 1904. Because the engine was nonreversible, an electric generator and a motor drive had to be used for maneuvering. By 1907, the *Circe* and the *Calypso* had more powerful 224-kW (300-hp) engines. The German navy followed, and during World War I, half of its submarines ran on MAN's four-stroke diesels, mostly 1,200-hp units (fig. 3.14). British and American navies also converted quickly, and no gasoline-fueled submarines were built after World War I.

The decisive breakthrough in commercial shipping came on November 4, 1911, when the Danish *Selandia*, the 6,800-dwt freight and passenger ship, became the first ocean-going vessel with diesel engines. It had two eight-cylinder, four-stroke, 783-kW (1,050-hp), 140-rpm engines built by Burmeister & Wain, Danish licensees in Copenhagen whose engine division was absorbed by MAN in 1980 (Marine Log 2009). Directly reversible diesels became available in 1906 (eliminating the need for a diesel-electric drive), but the *Selandia* was the first large ship to use them. It was delivered in February 1912, and its successful sea trials and its maiden journey to Tokyo via London (where Winston Churchill, at that time the First Lord of the Admiralty, inspected it), Genoa, Suez, and Bangkok (it returned to Denmark on June 26, 1912) led to a spate of new orders. In October 1912, the Danish shipyard delivered the *Fionia*, the first diesel-powered ship of the German-owned Hamburg-American Line.



**Figure 3.14**

A submarine diesel engine made by MAN for the German navy in 1917.  
Photograph from the MAN Bildarchiv.

The ship was renamed *Christian X* before its maiden voyage to New York, and a contemporary appraisal of its design and performance by an American engineer made it clear why the ascent of oil-powered shipping became irreversible (Bogert 1912, 4):

The steamship requires recoaling four times to circle the globe. . . . A fuel consumption of between nine and ten tons for each day . . . makes it possible for the *Christian X* . . . to make a continuous voyage around the world without replenishing her supply. Over 900 tons of oil can be run into her tanks, lying wholly below the cargo space. A steam engine ship would . . . require bunker space, . . . coal trimmers, firemen, and water tenders, all of whom are dispensed with in an oil-fired ship. . . . Of course, these are not gasoline engines but fuel-oil engines and utilize what is left after the gasoline and kerosene have been removed by distillation. . . . the extra cost of these . . . motor ships will have been earned and written off within eighteen months. . . . Altogether, the impression made on me from my sojourn in the engine room . . . and a careful perusal of the engineer's log . . . strengthen the conviction that marine history is being written by the advent of the Diesel engine.

The first two crosshead two-stroke engines (each rated at 625 kW) also went into service in 1912 on the German cargo ship *Monte Penedo*. They were made by the Sulzer Brothers at Winterthur. The company developed the first reversing two-stroke marine engine in 1905, and in 1910, it pioneered the use of the first valveless two-stroke marine engines with two 559-kW Sulzer machines on the Italian cargo ship *Romagna*. An unusual testimony to the reliability of marine diesels came from Roald Amundsen, whose expedition reached the South Pole in 1911. His steam-powered flagship the *Fram* was repowered in 1910 with a 134-kW Swedish-built diesel, and it proved an excellent choice.

In the middle of 1912, Diesel noted that “there is now a new verb in naval circles—‘to diesel.’ We do nothing but diesel, . . . they now say everywhere” (Diesel 1937, 421). This impression was confirmed by the rising capacity numbers. By June 1912, the total power of marine diesel engines in operation or under construction reached 1.72 million hp, and by the year's end that total rose to nearly 2 million hp built by some one hundred manufacturers around the world. At about 250 marks per horsepower, this already constituted an industry worth half a billion marks. And as the unit power of diesel engines grew, their efficiencies kept improving. In 1911, test of a larger (445 kW) engine indicated thermal efficiency of 41 percent, mechanical efficiency of 77 percent, and net efficiency of 31.7 percent (Clerk 1911).

After World War I, diesels rapidly completed their conquest of shipping propulsion. By 1925, nearly three-quarters of all new ship engines in Germany were diesels, and by 1939, a quarter of the world's merchant marine ships in service were propelled by diesel engines. Among the most important advances benefiting this market were the development of the first four-stroke diesel engine with an exhaust gas turbocharger (in 1924, by the Vulkan Yard in Stettin, a MAN licensee) and MAN's design of the first heavy-fuel oil-powered engine (in 1935). Although (as already noted) the dominant freighter of World War II was still a steam-powered ship, the post-1945 demise of marine steam engines was swift as diesel engines diffused widely to claim all but a small share of the commercial shipping and naval market. Large U.S. aircraft carriers are propelled by steam turbines (powered by nuclear reactors), and steam turbines and gas turbines also power some commercial ships, including liquefied natural gas tankers.

Yet another major advance in the transition to diesels was achieved before World War I. In 1913 came the completion and tests of the first large diesel-powered locomotive. When reporting the news, *Scientific American* (1913, 225) found it significant that this "first Diesel-operated locomotive should be not some engine designed to haul a suburban or slow train, but an express locomotive destined for service on the Berlin-Magdeburg trunk line." The engine was directly coupled to the driving axles, and an independent engine (with output equal to 20 to 25 percent of the main drive) was used to provide compressed air and to start the main engine or to boost its performance in high gradients. Two German railroad companies bought five of these locomotives before World War I.

The first railroad market that was captured after World War I by the new engines was for the machines that were used for yard switching (General Electric made the first switcher engine in 1923). After this came a gradual replacement of large mainline steam engines by diesel-powered locomotives, whose performance soon established new speed records. General Motors pioneered of this advance, thanks to the insistence of Charles Kettering on developing lighter and more powerful two-stroke diesels for cars (GM 1955; Young 1961). Kettering launched his program in 1930, and it soon produced a single-cylinder prototype. Two multicylinder units that were built for exhibition at the Chicago World's Fair in 1933 were only 20 percent of the weight of equally powerful traditional diesels. When the president of the Chicago, Burlington, and Quincy Railroad saw the

engines in Chicago he persuaded GM to use them for his new streamlined 92-passenger Zephyr train that began its scheduled service in April 1934. The 660-hp (447 kW) diesel powered an electricity generator whose current was used by two GE traction motors, and on May 26, 1934 the *Pioneer Zephyr* averaged 124 km/h on the more than 1,600-km-long run from Denver to Chicago, nearly halving the previous time (Ellis 1977). By the late 1930s, the country had ninety streamlined diesel-powered trains. Similar trains appeared in a number of European countries, but post-World War II developments took a different course. In freight service, steam locomotives were eventually displaced by diesels, but the world's fastest passenger trains (as well as many freight lines) have been energized by electricity (Smil 2006).

In 1935 GM built 16 two-stroke diesels for four new US Navy submarines (each one rated at 5,200 bhp), in 1938 it set up a new Detroit Diesel Engine Division to make the smaller diesels for trucks and buses, and during World War II it used a design with a vertical crankshaft (with four cylinders in every layer whose mass/power ratio was only about 1.8 g/W) in order to nearly double the cruising range of the Navy's submarine chasers.

Steam also continued to power most trains around the world for the first decade after World War II, but afterward steam locomotives began to disappear rapidly. In the United States, all but a few were gone by the end of 1958, and in Western Europe, they went out of service during the 1960s. But in China, many served on mainlines into the 1990s. But diesels did not capture the entire market because many European countries, Russia, and Japan came to rely heavily on electrified railroads. Road vehicles in general and automobiles in particular were the last means of transportation to adopt diesel engines. This slow tempo of adoption and diffusion did not reflect a lack of industrial interest, but it was a result of technical challenges and low-priced competition by gasoline vehicles. Diesel did not have a car engine uppermost in his mind when he began to work on his rational design. Nor did he have any great affinity for driving and maintaining new vehicles. He bought his first car (a red 24-hp NAG) in 1905, but given his engineering expertise, it is surprising that he was a poor driver and did not want to have anything to do with mechanical repairs (in this, he was like another great pioneer of internal-combustion machines, Gottlieb Daimler, who did not like to drive).

But Diesel had always expressed his hope that the new engine would eventually come to dominate the automotive market. On September 15, 1913, two weeks before his death, he wrote to his brother-in-law that “I still have a firm conviction that the automobile engine will also come, and then I will consider my life’s task finished” (Diesel 1937, 418). Although the first small diesel engine that was suitable for heavy road transport was built in 1908 by Heinrich Dechamps (and won a Grand Prix at the World Exhibition in Brussels in 1910), the machines were generally too bulky and too heavy, and (an important consideration for automotive use), available injection methods allowed only low rotation speeds and hence low power performance. In 1923, MAN’s three four-cylinder Otto car engines were converted to diesel by using the company’s newly developed high-pressure injection technology, and on March 12, 1924, one of these engines powered a 4-t truck on its trip from Augsburg to Nürnberg (fig. 3.15). The engine, which was displayed at the Berlin auto show in December 1924, was the first “definitely automotive diesel” (Williams 1972, 15). Benz and Daimler also introduced their own injection designs. But these were false starts, and the lasting breakthrough was achieved by another German company, whose innovations helped to create modern cars by introducing progressively better electric magnetos (generators producing a periodic electric pulse) to replace dangerous open-flame hot-tube ignition. Robert Bosch (1861–1942) opened his workshop for precision mechanics and electrical engineering in 1886, after his return from the United States, where he worked briefly for Thomas Edison (Heuss 1994).





**Figure 3.15**

The first truck with direct fuel injection was produced in 1924.  
Photograph from the MAN Bildarchiv.

Bosch's first successful product, a low-voltage magneto introduced in 1897, was followed by a high-voltage magneto and a new kind of spark plug invented by his employee Gottlob Honold (1876–1923) in December 1901. High-speed engines had finally become a reliable option. Because diesels did not require a spark to be ignited by a magneto, their future automotive adoption would have deprived Bosch of his main source of revenue, and hence the company began to develop diesel fuel injection for trucks in 1922. Its engineers were able to rely on its experience with lubricating pumps for car and stationary engines. They, much like a fuel pump, had to deliver a precise volume of fluid under high pressure (Schildberger 1951). The first pump prototypes were tested in 1923, and in 1926, Bosch offered the first devices for testing to interested German truck makers. Mass production of diesel injection pumps began in November 1927 (MAN was the first customer), and Bosch offered them as part of a complete system that also included requisite lines, fuel-supply pump, fuel filter, injection nozzles, and nozzle-holder assemblies (Bosch 2005).

Bosch delivered its one thousandth pump less than a year after the beginning of production, in October 1928, and by 1934, when it shipped 100,000 diesel injection pumps, virtually all German and many European manufacturers had adopted its design for their trucks, buses (first operated by Berliner Verkehrs-Aktion-Gesellschaft in 1930), and farm machinery. A diesel governor, assuring optimum fuel metering, was introduced in 1931, and special injection systems were also developed for locomotives, ships, airships (the Zeppelin era lasted from 1900 until the *Hindenburg's* fire in 1937), and the first diesel-powered airplanes. In 1932, MAN decided to concentrate only on Diesel engine production (MAN Diesel 2003), and by the late 1930s, most new trucks, buses, and tractors that were built in Europe had Diesel's engines.

Although Adolphus Busch was among Diesel's earliest licensees and enthusiastic supporters, America's largest automakers were relative latecomers to diesel production. This lag is understandable. The country was by far the world's largest producer of crude oil (in 1938, it extracted nearly 60 percent of global output, compared to less than 15 percent produced in 2006 by Saudi Arabia), whose plummeting price (in the wake of the discovery of a supergiant East Texas field in 1930) was arrested only by output restrictions enforced by the Texas Railroad Commission after 1931. Consequently, gasoline was abundant and cheap, and there was little interest in automotive diesels.

The Kenworth Motor Truck Company (set up in 1923 in Seattle) began producing the first diesel trucks in 1933, but the General Motors Corporation (GMC) established its diesel division only in 1938, and during the war years, most of its engines worked as generators in tanks, landing craft, and road-building machines. However, the company's greatest contribution to victory in World War II, its CCKW truck, was powered by a 94-hp, 4.4-L gasoline engine (model 270). Clessie Cummins (1888–1968) was the diesel's American pioneer (Cummins 1967). He demonstrated the first passenger designs in the late 1930s, and the company that he founded (headquartered in Columbus, Ohio) remains one of the world's leading makers of heavy automotive engines.

Bosch had small pumps for passenger cars ready by the late 1920s, but the world's first diesel-powered car and the first diesel car, Mercedes-Benz 260D, was not introduced until 1936 at the Berlin car show. This rather heavy, 33.5-kW (45-hp), four-cylinder, six-seat saloon car soon became the

capital's favorite taxi (Williams 1972). Two now defunct German companies (Hanomag and Saurer) also produced first diesel-powered cars in 1936, and Peugeot joined the list before World War II. But diesel cars captured only a tiny share of the market and after the war their diffusion foundered because of the very low (and in real terms declining) cost of gasoline, their reputation for sluggish performance, engine noise, vibration, and higher emissions of particulate matter and sulfur dioxide. For many years Mercedes-Benz and Peugeot were the only automakers producing limited numbers of diesel cars.

The first round of the oil-price rises that were driven by the Organization of the Petroleum Exporting Countries (1973–1974) made diesel-powered cars more appealing, and the availability of Bosch's new distributor injection pump (first developed in 1962) improved the prospect of their wider adoption. In 1976, Volkswagen introduced a diesel-powered version of its Golf (the Rabbit in North America) with a 1.47-L, 37-kW, and 5,000-rpm engine.

As with all prime-mover transitions, the shift to diesels—the replacement of steam engines and, to a lesser extent, of gasoline-fueled machines—was a necessarily gradual process that took generations to accomplish and that proceeded at different paces in Europe, North America, and Asia. The engine's conquest of all market niches where it could be competitive began with light stationary applications and the first marine uses before World War I, but by 1912, it was clear that nearly all future ships would be diesel-powered. Large numbers of diesels entered high-speed railway service in the 1930s, and in the 1940s and 1950s, they took over heavy-duty railroad freight. Automotive uses were the last to be converted, starting with trucks in the late 1920s and 1930s, but large-scale deployment of passenger diesels had to wait until the 1970s. In contrast, the gas turbine—the other quintessential prime mover of modern globalization—had a much steeper ascent to commercial dominance.

# 4

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## Gas Turbines

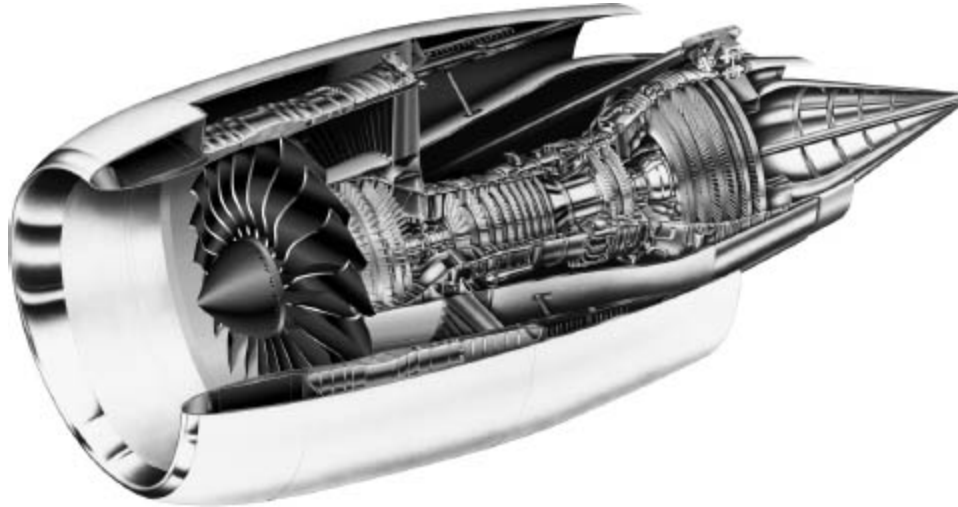
I have allowed the patent to lapse. Nobody would touch it on account of the enormous cost of the experimental work, and I don't think they were far wrong, though I still have every faith in the invention. However, if anybody were keen on taking it up I should think it would pay them. There is no doubt in my mind that, as things stand at present, it is the only way to high altitude flying.

—Frank Whittle in a letter to R. D. Williams, May 7, 1935

When Frank Whittle wrote to R. D. Williams in the spring of 1935, prospects for developing his patented gas-turbine design were poor, but it did not take long before every opinion set down in that letter became a reality. The engine's development did indeed cost a great deal of money, but the companies that eventually undertook it helped to pioneer a new and a highly profitable megaindustry, and it was the only way to fly high, above the weather, and close to the speed of sound. After the first practical prototypes of aircraft turbines were tested, their subsequent commercialization was very rapid. This feat was made more remarkable given the gas engine's mechanical complexity, its demand for materials of unusually high quality and durability, and the fact that its development took place twice, and entirely independently, in Britain and in Hitler's Germany.

That was where the first experimental flight of gas-turbine-powered military aircraft took place in 1939. The first combat jets, British and German, went into service in July 1944, the first multiengine bomber (the American B-45 Tornado) flew in 1947, and the first commercial jet (the British Comet) took off on test flights in 1949 and with passengers in 1952. As a result, the gas turbine became the only new fossil-fueled prime mover that was commercially introduced in the twentieth century. The two other internal-combustion engines (gasoline-fueled and Diesel's machines) dated, respectively, to the 1880s and 1890s, and Parsons's steam turbine also began its development in the 1880s. *Gas turbine* is actually a misnomer because the engine can burn liquid fuels as well as gases. And although it belongs to a critically important family of internal-combustion engines, its

operation differs from all Otto-cycle gasoline and diesel engines in three fundamental ways (Bathie 1996; Langston and Opdyke 1997; Saravanamuttoo, Rogers, and Cohen 2001).



**Figure 4.1**

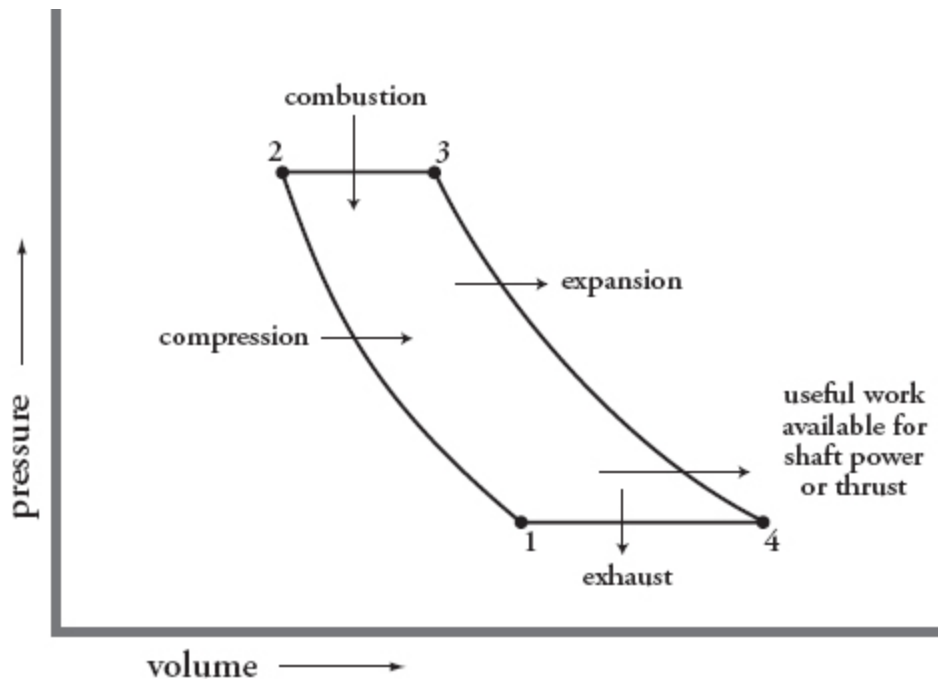
The principal components of a modern aviation gas turbine illustrated by a trimetric view of General Electric's GE90-115B engine.

Reproduced courtesy of GE Aeroengines.

In those engines, compression takes place inside a cylinder where the fuel ignites (either by a spark or by high pressure), but in turbines the air compression is accomplished before the addition of fuel in a combustor. In gasoline and diesel engines, combustion is intermittent, while in gas turbines, it proceeds continuously. And although both gasoline and diesel engines transfer the kinetic energy of expanding gases via reciprocating piston motion to a crankshaft, in gas turbines part of the energy of the hot high-pressure gas leaving the combustor is extracted by rapidly rotating circular blade assemblies. All gas turbines must have four principal parts—a compressor, a combustor (combustion chamber), a turbine, and an exit nozzle (fig. 4.1).

As the incoming air is compressed (in early engines, the overall compression ratio was less than 5 to 1, while modern engines compress the incoming air to more than thirty or even forty times the atmospheric pressure), its temperature is raised to more than 500°C. As the air is forced through the combustion chamber, fuel is added and ignited, the temperature of the generated gas surpasses 1,000°C and a portion of its kinetic energy is

used to drive the turbine—which, in turn, drives (via a rotating shaft) the load, which may be a compressor of an aeroengine, a ship’s propeller, or (with stationary turbines) an electric alternator. In the latter two cases, as much of the kinetic energy of the hot gas as possible should be converted to drive the load.



**Figure 4.2**  
A Brayton cycle graph.

In aeroengines, the goal is opposite—to use as little of the kinetic energy of the hot combustion gas to power the compressors so that the largest possible mass of hot and rapidly moving gas can exit the engine’s nozzle and generate a powerful thrust to propel the aircraft. The higher the momentum of the gas exiting the engine, the higher the thrust. A graphic representation of a gas turbine is given by the ideal Brayton gas cycle (fig. 4.2), and theoretical thermal efficiency is expressed as  $\eta = (T_3 - T_4) - (T_2 - T_1) / T_3 - T_2$ , where  $T_1$  to  $T_4$  are, respectively, temperatures (all in degrees Kelvin at the compression inlet, compression outlet, turbine inlet, and turbine outlet).

Technical details regarding the design, operation, and performance of the modern gas turbine used to power airplanes are available in Hill and Peterson (1992), Cumpsty (2003), and Gunston (2006), and detailed

summaries and reviews of individual engine parameters are now readily accessible on the Web sites of the three leading manufacturers—General Electric (GE), Pratt & Whitney (P&W), and Rolls-Royce (RR). I introduce here a few key technical terms that describe some principal components of these complex machines and several key indicators that are commonly used to quantify the performance of aeroengines and to compare their merits (their evolution is reviewed later in this chapter and the next chapter).

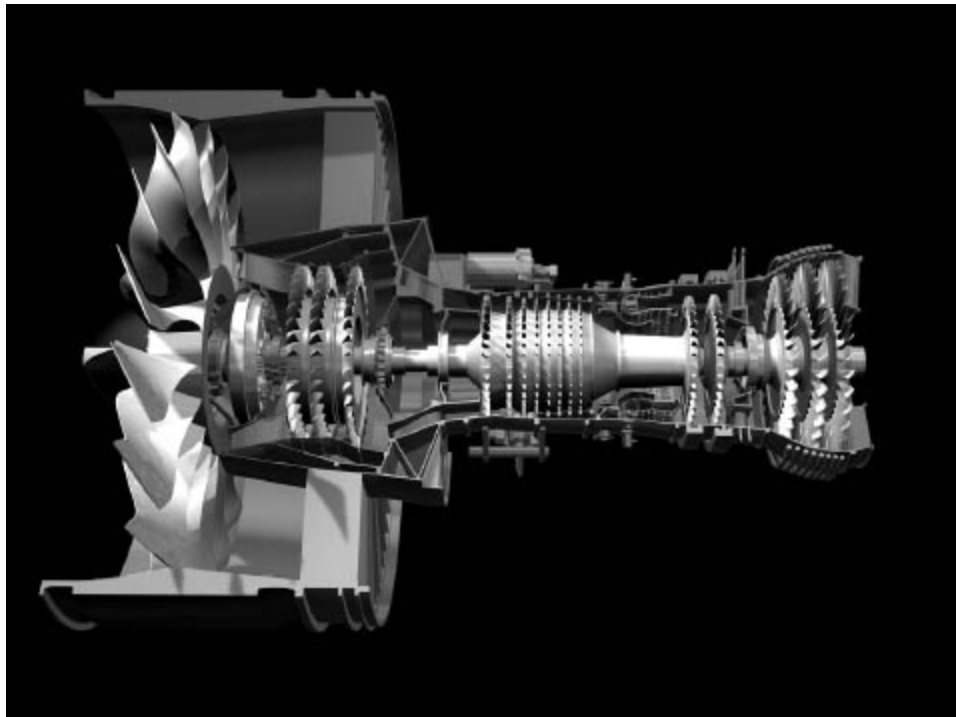
A high net thrust requires either a high jet speed or a large air flow or a combination of the two. Thrust ratings—traditionally expressed in pounds of force (lbf) or, in *Système International* (SI) units, in kilonewtons (kN)—are normally given for the performance of a stationary (grounded) engine. They indicate the maximum power that is available during the acceleration to takeoff (jetliner engines are not permitted to work continuously for more than five minutes at this peak rating). However, the top-of-climb thrust (as the climbing aircraft nears its cruising altitude) is the critical value in engine design.

In all long-distance flights, most time is spent in the cruising mode, when the engines deliver only a fraction of their maximum thrust. For example, the four JT9D Pratt & Whitney engines that powered the early Boeing 747 had the combined maximum (takeoff) thrust of 973 kN, but when the plane was cruising at just over 12 km and averaging about 910 km/h, it required a total thrust of only about 245 kN—a quarter of its maximum performance. The difference is even greater with the latest high-bypass turbofan engines: the cruising thrust of GE 90 is only about 18 percent of the engine's enormous takeoff thrust (its different versions range from 375 to 512 kN).

The overall efficiency of a gas-turbine aeroengine is the product of its thermal and propulsive efficiencies. The thermal efficiency is the ratio of the increase of induced kinetic energy (which is proportional to the square of air speed) and the chemical energy of the combusted fuel. The propulsive efficiency is calculated as a product of the thrust and forward speed divided by the increase of kinetic energy. With jet velocities typical of large gas turbines (about 400 m/s) and cruise speed of about 250 m/s (900 km/h) at an altitude of 10.5 to 11 km, the propulsive efficiency is in excess of 75 percent, but losses in turbine and fan drives reduce this by more than a third to no more than 47 percent. Overall efficiency was no higher than about 10 percent for Whittle's first practical turbojet design of the early 1940s. By the early 1950s, it rose to 15 to 18 percent, by the mid-1960s turbofan

engines with low-bypass ratio rated up to 25 percent, later high-bypass-ratio engines elevated the performance just above 30 percent, and today's best machines come close to 40 percent.

The turbine and compressor can be connected simply by a single shaft, or a longer, more slender shaft can rotate inside a larger-diameter shaft, and the two shafts are connected, respectively, to low- and high-pressure segments (spools) of the turbine and the compressor. In addition to this two-spool arrangement, it is also possible to have three spools with an intermediate-pressure stage. Among today's large aeroengine makers, only Rolls-Royce offers this arrangement. The other two companies make only twin-spool turbines. Gas-turbine compressors are either centrifugal or axial. Centrifugal compressors have a central rotating disk (impeller) with radial vanes that is surrounded by a diffuser within a casing. Axial compressors alternate rotating rings with spokelike curved blades (rotors) and stationary rings of blades (stators). The simplest gas turbine has a single-stage centrifugal compressor that is powered by a single-stage axial turbine. Today's large aeroengines have multistage axial compressors (often with more than ten stages unevenly divided between low- and high-pressure segments) that are driven by multistage axial turbines that are similarly divided between low- and high-pressure sections ([fig. 4.3](#)).





**Figure 4.3**

Multiple compressor and turbine stages are clearly illustrated on this cross-section of Pratt & Whitney's Pure Power 1000G engine, which shows (from left to right) (1) a fan, (2) three stages of a low-pressure compressor and eight stages of a high-pressure compressor, and (3) two stages of a low-pressure turbine followed by three stages of high-pressure turbine.

Image available at the Pratt & Whitney Web site.

Low specific fuel consumption is an obvious design goal, but as more efficient engines are heavier, there is an inevitable tradeoff between energy use and engine size. Gas turbines are particularly attractive for powering large aircraft because they have a much higher specific power output (that is, output related to the engine mass, g/W) than reciprocating machines. Orville and Wilbur Wright accomplished their first flight with an engine of their own design whose mass-to-power ratio of about 8 g/W. Rapid improvements brought the ratio down to 1.34 g/W for the Liberty, the best U.S. World War I engine, and the best World War II reciprocating aeroengines (such as the Wright Cyclone) rated less than 0.7 g/W—but Whittle's pioneering W.1 turbojet of the early 1940s needed just 0.38 g/W, early commercial turbojets of the mid-1950s rated about 0.25 g/W, and the latest turbofan weigh less than 0.1 g/W.

No other prime mover has seen such a rapid rate of commercialization as gas turbines in flight. Their development can be fortuitously divided into distinct decades. The first period, 1936 to 1945, entails the years of pioneering designs and tests of gas turbines in the United Kingdom and Germany and the deployment of first turbojets in military aircraft. The second period, 1946 to 1955, encompassed the years of rapid performance advances of turbojet engines, their deployment in many fighters and bombers, and the beginning of the commercial turbojet era. The third period, 1956 to 1965, saw the real beginning of turbojet-driven commercial aviation, the rapid conversion from piston aircraft to jetliners in long-distance flight, and the introduction of the first turbofan engines. The fourth period, 1966 to 1975, witnessed the maturation of aviation gas-turbine design with the triumph of large turbofans leading to the birth of inexpensive, mass-scale intercontinental airline travel in wide-body jetliners.

**The Remarkable Origins of Jet Propulsion**

As with many other great technical ideas, the first proposals for gas turbines preceded by decades the first designs of practical machines. The principle of such an engine was patented for the first time in 1791 by John Barber in England, but at that time there was no possibility of building such a machine because there were no requisite alloys and precision manufacturing procedures. Even a century later, when a number of European scientists and engineers first attempted to build such engines, it was still an elusive challenge. In 1872, Franz Stolze proposed a complex machine with a ten-stage axial flow compressor and a fifteen-stage axial flow turbine, patented it in 1899. His designs embodied the essential configuration of modern multistage machines, but they barely produced any net power (New Steam Age 1942).

In 1882, Aegidius Elling in Norway began to build his simpler, six-stage centrifugal compressor machine, which in 1903 eventually produced a small amount of power. In the United States, Sanford Moss (1872–1946) made his first design proposal in 1895 and by 1907 built a laboratory prototype at General Electric. Charles G. Curtis received his patent for a gas-turbine engine (U.S. 635,919) in 1899 (Conner 2001). Promising advances (but no industrial breakthroughs) were made during the first decade of the twentieth century. Between 1903 and 1906, the Parisian Société des Turbo-moteurs (Auguste Rateau, Charles Lemale, and Rene Armengaud) designed and built several machines. Their best design of a continuous gas turbine had a twenty-five-stage centrifugal compressor. The engine's combustion chamber was lined with carborundum (marking the beginning of using highly temperature-resistant materials in gas turbines), and the machine was cooled by water. Its useful output was 82 hp (about 61 kW), and its efficiency was less than 3 percent.

Almost concurrently, between 1905 and 1908, the Swiss company Brown Boveri (by that time, an early leader in steam turbine design) completed its first prototype based on the designs of Hans Holzwarth. But all of those early experimental machines either produced no net power or had efficiencies inferior even to those of steam engines and all of them (except for the Curtis patent for an automotive propulsion) aimed at stationary uses to fill some of the same niches that were being taken over by rapidly improving steam turbines. Consequently, the established steam turbine makers Brown Boveri and General Electric emerged as the gas-turbine design leaders. The systematic commercial development of American

stationary machines began in 1917, when Sanford Moss set up a turbine research department at General Electric's steam turbine factory in Lynn, Massachusetts.

The first practical result of this work was a turbo supercharger that used hot exhaust gases from a reciprocating aeroengine to drive a centrifugal compressor. This arrangement boosted the power of Liberty engines, the dominant prime mover of the U.S. World War I air force in Europe, by slightly more than 50 percent. In May 1921, Maxime Guillaume filed a French patent application for a turbojet engine (*propulseur par réaction sur l'air*), but it turned out to be another theoretical exercise without any practical results. And in 1926, Alan Arnold Griffith at the Royal Aircraft Establishment at Farnborough began to work on the idea of a gas turbine that could power a propeller aircraft, also without any practical results.

By that time, engineers had decades of experience with various designs of highperformance water turbines and steam turbines, but no real progress could be made in building commercially acceptable gas turbines for mobile applications until the development of better combustors—until compressors became more efficient and until new, lightweight, yet highly heat-resistant alloys introduced in the 1930s made it possible to withstand high turbine temperatures. By 1928, Holzwarth's small gas turbine made by Brown Boveri was installed in a German steel mill, and in the early 1930s it became realistic to think about larger stationary gas turbines for industrial application. There appeared to be no imminent prospects for a breakthrough in designing turbines for flight. But during the second half of the 1930s, the outlook changed dramatically thanks to the inventiveness and dedication of two young engineers.

This conclusion does not mean that I see the introduction of gas turbines in flight simply as another example of the heroic pattern of technical innovation—as a process driven overwhelmingly by brilliant and persevering individuals. I have already noted decades of preceding work, and in this chapter I explain the depth of organizational and institutional support that made their deployment and eventual commercialization possible. Still, these facts cannot detract from exceptional contributions made by Frank Whittle, the engine's great British pioneer (fig. 4.4), and by Hans Joachim Pabst von Ohain, its German inventor. Their invention of gas turbines for flight provides (together with Alexander Graham Bell's and Elisha Gray's patenting of the telephone and Charles Hall's and Paul

Héroult's introduction of aluminum smelting) one of the most momentous examples of parallel innovation. Moreover, both Whittle and von Ohain began their work as outsiders, and their efforts did not generate any immediate interest from established engineering companies, whose expertise was needed to turn the new ideas into reliably working prototypes.

Their contest was not as close as Bell's and Gray's patent filing on the same day, February 14, 1876. And the complexity of the machine made it impossible to turn the concept into a working prototype as rapidly as Hall's and Héroult's electrode furnaces, which were patented in 1886 (Smil 2005). Because of the outcome of World War II, von Ohain's pioneering efforts became much less known than Frank Whittle's work. Von Ohain's work, as well as the work on other German jetpropulsion projects, ended abruptly with the Nazi defeat in 1945, and the country's technical head start in advanced aviation (besides new engines, German designers also pioneered streamlined bodies and swept wings) did not translate into a new military and commercial peacetime industry. That role was filled by the British and American engine and aircraft makers.

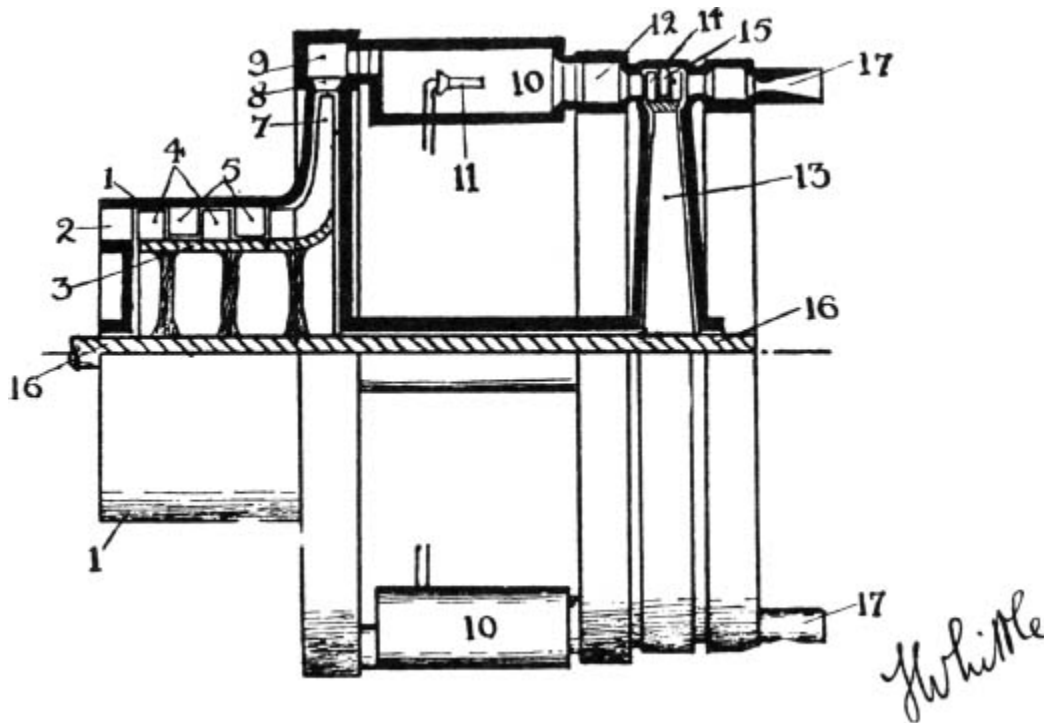
Frank Whittle (1907–1996) began his Royal Air Force career as a boy apprentice in 1923, and in 1926, he began training as a pilot. He became a pilot officer in 1928 (ranked “exceptional to above average”), the same year that he won a prize for aeronautical sciences and began to formulate his ideas about a radically new way of aircraft propulsion (Golley and Whittle 1987). His 1928 Royal Air Force College term thesis was entitled “Future Developments in Aircraft Design,” and in it Whittle foresaw the turbine as the most efficient prime mover for fast, high-flying airplanes. Less than two years later, on January 16, 1930, he filed his first patent application (UK 347,206) for a turbojet engine with a centrifugal compressor and reverse air flow (fig. 4.5).



**Figure 4.4**

Frank Whittle during his early Royal Air Force days and after World War II. Photographs by the *Coventry Telegraph*.

The cross-section illustrates a deceptively simple machine. Annular inlet (2) leads to a two-stage axial compressor (4) that is followed by a single-stage centrifugal compressor (7). Compressed air is led through a diffuser (9) to parallel combustion chambers (10), where the fuel injection takes place (11), and the hot gas flow drives a two-stage axial flow turbine mounted on a single disc (14) with stator vanes (15) separating the two rotors. As the turbine rotates, it drives the compressor mounted on the same shaft (16), and the gas exits through a nozzle (17). Initial expectations were for a machine that could develop maximum static thrust of 6.2 kN (1,389 pounds of force) and handle about 11.8 kg of air per second.



**Figure 4.5**

A cross-section of Whittle's simple turbojet engine in his January 1930 patent application (UK 347,206). The engine's main components are (from left to right) two axial rotor (4) and stator (5) stages, a centrifugal impeller (7), a 90° elbow and outlet vanes (9), multiple tubular combustion chambers (10), a fuel burner (11), a turbine rotor (13), a drive shaft (16), and multiple nozzles (17).

This patent filing led to no commercial interest in the invention. As a result, when the patent came for a renewal in 1935, the Air Ministry refused

to pay the requisite £5 fee, and Whittle, at that time studying mechanical engineering at Cambridge University, let the patent lapse (see the chapter's epigraph). Not long afterward, Whittle was approached by a former fellow pilot, R. D. Williams, who helped to arrange the necessary financing for a new company that would undertake the engine's development. Power Jets Ltd. was incorporated in March 1936 with a single objective—to prove that a single-shaft turbojet with a single-stage centrifugal compressor could become a new prime mover of military aircraft.

Whittle's mastery of thermodynamics and aerodynamics was the critical component of this endeavor. Whittle's work thus belongs to the same class as Parsons's and Diesel's innovative designs, which proceeded from scientific understanding to practical machines. As Stanley Hooker (1907–1984), jet-engine designer at Rolls-Royce, put it, Whittle was able to lay down the engine's performance “with the precision of Newton” (Fulton 1996). If anything, his task was made harder than Diesel's or Parsons's challenge by the need to overcome the combined challenge of designing a machine with unprecedented attributes. Its combustion intensity, pressure ratio in a centrifugal blower, mass-to-power ratio, and material endurance set new records. The difficult process of converting the idea into a working prototype of a new aeroengine was described in detail by the inventor (Whittle 1953), is critically examined in two monographs (Golley and Whittle 1987; Nahum 2004), and is reviewed in chapters or sections of volumes devoted to the origins and the accomplishments of jet propulsion (Smith 1944; Neville and Silsbee 1948; Heimann 1963; Constant 1980; Jones 1989; Younossi et al. 2003).

The standard account, established by Whittle's 1953 book (and repeated by most of the British obituaries in 1996), relates the many setbacks and disappointments that he encountered when dealing with official representatives (whether military or civilian) before and during the war (“obstruction from the authorities” as the *Daily Telegraph* put it in 1996) and that culminated in the wartime nationalization of Power Jets. These events certainly contributed to Whittle's long hospitalization in 1944, and the need to deal with a number of governmental agencies undoubtedly played a role in delaying the serial production of service-ready engine models. But as Nahum (2004) convincingly relates, assorted bureaucracies showed some flexibility and originality in fostering the new engine, and overall, Whittle was treated “with considerable indulgence” by the Air

Ministry as well as by the Ministry of Aircraft Production. Instead of revisiting these (still far from fully resolved) matters, I simply note the major milestones on the British path to practical jet power.

The first experimental engine, the Whittle Unit (WU), had a single large, doublesided centrifugal compressor (the patented design with an axial compressor was simply too difficult to build), its impeller had thirty blades, separate streams of compressed air had to make a 90-degree turn to enter a single combustion chamber, and the hot gas exited with constant momentum. The British Thomson-Houston Company (BTH) was given the contract to build the engine. The first successful bench test took place on April 12, 1937, and trials continued until August 1937. A reconstructed WU, ready in April 1938, had actual compressor and turbine efficiencies of 70 percent, air-mass flow of nearly 12 kg/s and thrust of 4.4 kN. The next model, the WU2, ready on April 16, 1938, was strangely complicated. Compressed gas was driven into ten curved pipes to the engine's rear, where the fuel injection took place. The air and flame then made their first 180-degree turn as they traveled forward and then made the second complete reversal before impacting the turbine impeller.

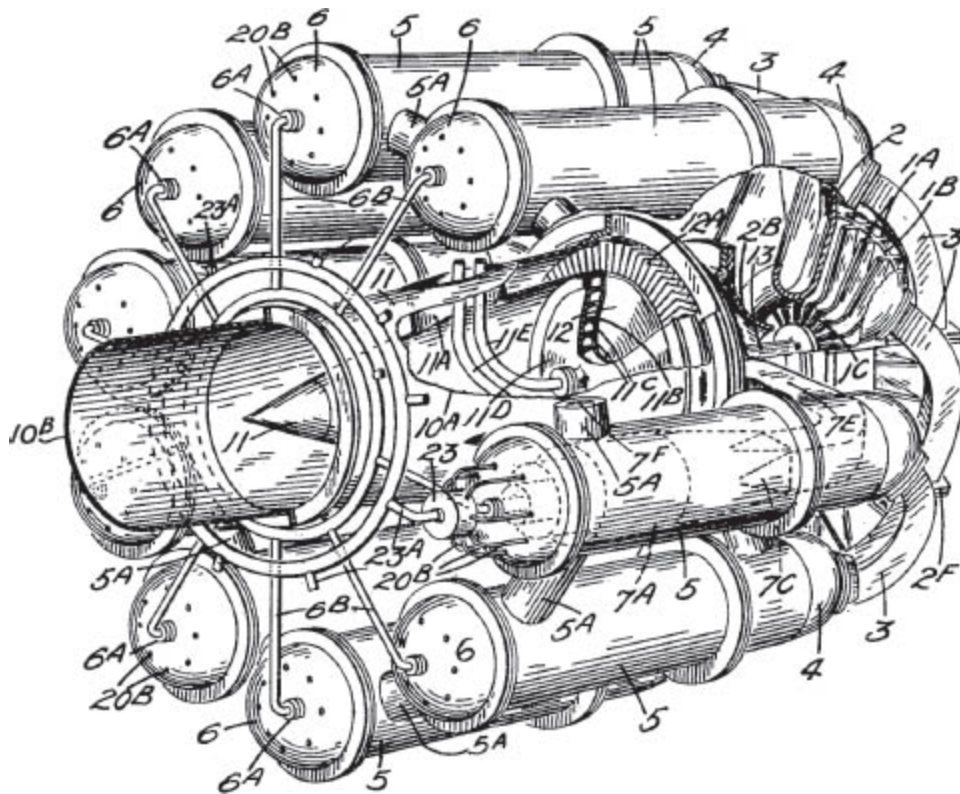
The WU Model 3, ready in October 1938, had ten separate combustion chambers with a reverse-flow layout. Its drawing is attached to Whittle's application for the British patent filed in December 1939 and the U.S. patent filed in February 1941 (fig. 4.6). On June 30, 1939, the engine ran at 16,500 rpm, which justified proceeding with the design of an actual flight-ready turbojet. The top performance of the later W.1 models was 17,000 rpm, air-mass flow of nearly 10 kg/s and 4.2 kN of thrust. The W.1A engine almost reached the design specification of 6.4 kN of thrust, and it also had much lower specific fuel consumption. This engine was mounted on an experimental body made by the Gloster Aircraft Company (and the airplane was designated as the Gloster E.28/29). After the first taxiing runs and short (about 200m) hops that were done on April 8, 1941, Gerry Sayer, the test pilot, noted that the engine was "very smooth indeed, and no vibration was observed in the pilot's cabin" (Golley and Whittle 1987, 167).

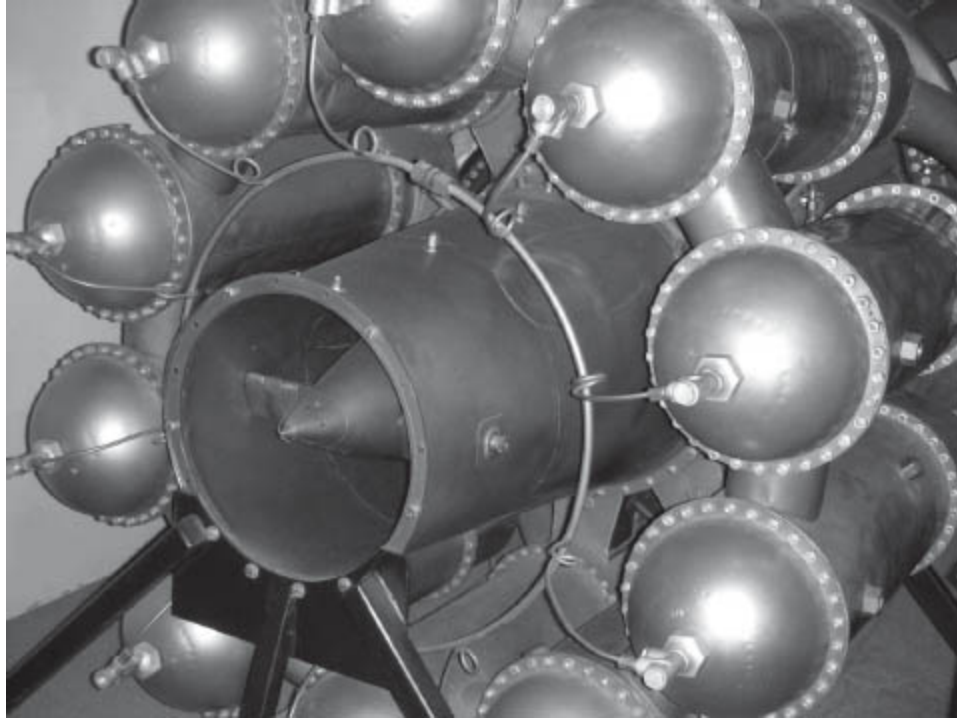
The first powered British jet flight took place at the RAF Cranwell base (coincidentally, the very place where cadet Whittle wrote his term thesis on jet propulsion thirteen years earlier) on May 15, 1941. Sayer became airborne after less than 600 m, soon disappeared behind the clouds, and ended the uneventful seventeen-minute flight with some steep gliding turns



and a perfect landing. Whittle's famous comment—as the plane took off and somebody slapped him on the back and said, "Frank, it flies!"—was "Well, that was what it was bloody-well designed to do, wasn't it?" (Golley and Whittle 1987, 170). The only pictures taken were with an amateur hand camera, and there is no film of the first flight.

The W.1X engine was first tested in December 1940, and it helped to launch jet development in America. On October 1, 1941, it was dismantled, crated, and sent to the General Electric engine factory in Lynn, Massachusetts, marking the beginning of the wartime transfer of the British jet-propulsion know-how to the United States. The first American jet, the XP-59A Airacomet, made its first flight a year later on October 2, 1942, actually beating the British Meteor by five months. However, its overall performance (and its thrust of just 5.6 kN) made it inferior to the best propeller-driven planes of the day (the Republic P-47D and the North American P-51D Mustang).





**Figure 4.6**

Whittle's drawing of a turbojet (WU Model 3), which accompanied his U.S. patent application of February 1941 and a close-up photograph of a nearly identically looking W1X engine from 1941 displayed at the National Air and Space Museum in Washington, DC.

The drawing is available from the U.S. Patent and Trademark Office. Engine photo by V. Smil.

Whittle's design proved to be influential. Not only did it provide the beginning of the subsequently large U.S. jet-engine industry, but Whittle-derived engines were made under license throughout the Western world, and after Rolls-Royce sold one of its early jet engines to the Russians, they were reverse engineered (and later licensed) in the Soviet Union and China, eventually powering nearly 100,000 military and commercial airplanes worldwide (Fulton 1996). All of the world's leading gas-turbine manufacturers—General Electric, Pratt & Whitney, and Rolls-Royce—set up their jet-aeroengine divisions by producing designs of Whittle's turbojet. In contrast, the pioneering work of Hans-Joachim Pabst von Ohain (1911–1998), who converted his ideas into the first jet engine to propel a plane, had only a short-lived impact. Von Ohain's own work and the subsequent development of engines that were based on his design came to abrupt ends by the defeat of Hitler's Germany in 1945.

Von Ohain (fig. 4.7) conceived a new mode of aircraft propulsion in 1933, at almost exactly the same age as Whittle, in his seventh semester as

a student of engineering at Göttingen, where he got his doctoral diploma in November 1935 (Conner 2001). His first patent for jet propulsion was granted in the same month. Von Ohain and his patent attorney were unaware of Whittle's work and of Guillaume's 1921 patent, whose existence, as von Ohain later noted, "should have been the cause for the rejection of practically all further turbojet patents" (Conner 2001, 34). In March 1936, after securing a letter of recommendation from one of his professors, he approached Ernst Heinkel in Rostock.

Heinkel was already Germany's leading aircraft (but not aeroengine) designer (his HE 111 bombers were used in the Spanish civil war) when the young physicist came to him with, as he put it, an idea to revolutionize his business. Heinkel almost immediately engaged the twenty-four-year-old enthusiast, and von Ohain brought along to the company Max Hahn, his friend and a garage mechanic who helped him to build the engine's first (failed) test prototype. Von Ohain decided to use hydrogen as the best fuel to demonstrate the jet principle, and the successful trial of the HE S1 engine took place in Heinkel's plant in March 1937, a month ahead of Whittle's first test. Heinkel's design group took just two years to develop the world's first centrifugal-flow turbine for flight.

Von Ohain's team immediately began its work on the first, gasoline-fueled, flight engine. The engine, the HE S3B, reached the required thrust in early August 1939, and it was mounted on an experimental aircraft designed by Heinkel (later designated the Heinkel-178). On August 27, 1939, Erich Warsitz took off on the first test flight at a maximum speed of about 600 km/h for some 50 km. Five days later, Hitler attacked Poland and began Germany's most destructive war. Heinkel's company built many planes to aid this aggression, but jet-powered fighters or bombers were not among them. When the war started, Germany already had five other research programs working on different designs of jet engines, and one of them (at Junkers Motoren) led to the world's first serially produced jet engine that was used to power a fighter plane. The development of von Ohain's HE S8 engine, destined for the Heinkel HE 280 (the world's first twin-engine turbojet fighter), was underfunded and encountered many problems, and only nine units were built.



**Figure 4.7**

Hans-Joachim Pabst von Ohain in the early 1930s, when he began to work on jet propulsion. The photograph reproduced by permission of the National Air and Space Museum, Smithsonian Institution.

As for the two bold pioneers, their postwar careers took very different paths. Whittle, who handed over £47,000 of his shares in Power Jets during the company's wartime nationalization, retired from the Royal Air Force in

1948 on medical grounds and never returned to work directly on any new jet designs. Kings Norton, in his appreciation written for the 1948 Royal Commission, rightly concluded that the jet-propulsion engine would have come without Whittle but much later. Nahum (2004, 163) put it best: “It was Whittle’s passion, in all senses, that established the national will to treasure and keep faith with the jet.”

Von Ohain became one of the small army of German technical experts who were brought by the U.S. armed services to America to continue their engineering and scientific work. He arrived at Wright Field in Dayton, Ohio, in February 1947, and he stayed at the Wright-Patterson Air Force Base until his retirement in 1979, working on problems ranging from thrust augmentation to direct energy conversion. Both men got their share of national and international honors. They eventually met—for the first time in 1966 and then in 1974 (fig. 4.8)—but neither had any direct impact on the post-World War II advances in commercial aeroengines. Those innovations have come from the large R&D teams of the world’s three leading designers and builders of gas turbine aero-engines—from General Electric’s aeroengine division (headquartered in Cincinnati), Pratt & Whitney (whose headquarters are in Hartford, Connecticut), and Rolls-Royce (whose world headquarters are in London).

### **The Commercialization of Turbojets**

The two pioneers of jet propulsion were thus destined to share what was perhaps an inevitable consequence of their effort—exclusion from the development of serially made engines. After the successful flight of the Gloster E.28/29 on May 15, 1941, Power Jets developed the W.2B engine for the new Meteor fighter, and the Rover Company was selected for its serial manufacture, only to be replaced (in December 1942, after strained relations with Power Jets and production delays) by Rolls-Royce, a more reliable contractor. Whittle’s pride in the great simplicity of his engine did not impress the company’s chairman, who told the inventor that “We’ll bloody soon design the simplicity out of it” (Golley and Whittle 1987, 179).



**Figure 4.8**

Whittle and von Ohain meeting at the Smithsonian Institution on October 24, 1974.

Photograph reproduced by permission of the National Air and Space Museum, Smithsonian Institution.

But the company did so in a manner that has made it a lasting leader in jet design (Roll-Royce 2009). Since June 1939, Rolls-Royce had its own gas-turbine program led by Alan Arnold Griffith and aimed at the development of an axial-flow machine. By early 1940, de Havilland became the third British company to work on jet propulsion, and it produced the second British turbojet—the centrifugal H-1 (named after its designer Frank Halford), which was similar to Whittle’s machine. In 1944, when Geoffrey de Havilland intended to use the engine in his Vampire jet, it was renamed Goblin. This prototype of the Gloster Meteor, powered by two Rolls-Royce-built W.2B engines (each with 7.6 kN of thrust), flew for the first time on March 5, 1943, and the plane finally entered the service in July 1944. Its first use could not have been anticipated. Because of its top speed of nearly 770 km/h a pilot could align it with a German V1 missile, flip the missile on its back with the plane’s wing, and abort the V1’s trajectory (Walker 1983).

In Germany, Hitler’s Air Ministry selected the Messerschmitt company to produce the first jet fighter powered by the world’s first mass-produced jet engine (Jumo 004), which was designed in 1942 at Junkers by Anselm Franz (1900–1994), the company’s chief engineer. After the war, Franz was



brought to the United States, where starting in 1951 he directed at Avco Lycoming the development of gas turbines for helicopters, including the engines for the Cobra, Mohawk, and Bell and a massive turbine for the M1 Abrams main battle tank. He retired as the company's vice president in 1968, one of several prominent German engineers and scientists who served Hitler, Eisenhower, and Kennedy.

The Jumo 004 was an axial-flow turbojet, and the Messerschmitt Me-262 (Schwalbe) was flight-tested in March 1942 and had its first combat mission on July 25, 1944 (Wagner 1998). Of more than 1,400 Me-262 jets that were built, only about 300 were deployed before the end of World War II, and although the plane's technical performance was superior to that of British or U.S. fighters (even until 1947), it had a high rate of operational failure (Meher-Homji 1997). Jet propulsion entered the war too late to make any difference on either side, but the inherently low weight-to-power ratio of gas turbines and their increasingly powerful thrust made them the unrivaled prime-mover choice for all post-World War II fighters and bombers and for commercial (passenger and freight) aviation.

The postwar development of military engines (driven after 1947 by the cold war rivalry) has been well summarized in general terms by Gunston (2006) and in technical details by Younossi et al. (2003). And while its review is outside of this book's scope, it is clear that all early commercial engines were direct derivatives of successful military designs that were introduced during the late 1940s and the early 1950s (Loftin 1985; Gunston 2006). The dedicated development of increasingly more powerful engines for passenger jetliners came only after the first generation of jetliners entered regular service during the late 1950s. Right after the war, with the total ban on Germany's advanced gas-turbine R&D and with the United States pursuing only military applications, the United Kingdom was the lone determined pioneer of commercial jet aviation—but this head start was lost by the late 1950s.

The British road to commercial jet flight began with a wartime committee chaired by Lord Brabazon (1884–1964), a former minister of aircraft production (Phipp 2007). Its work began in February 1943 and culminated in a series of reports published between November 1943 and August 1945. They identified four airliner designs for postwar development—a large trans-Atlantic piston airliner (a type of aircraft soon to be an anachronism), a short-haul piston or turboprop plane, a medium-range

airliner, and a long-distance jetliner (an option favored by Geoffrey de Havilland, who wished to capitalize on his company's wartime work on the Goblin turbojet). Contracting for different types of planes began in 1944, and de Havilland began to develop the Comet, a four-engine airplane for the British Overseas Airways Corporation (BOAC), which ordered fourteen of them in 1946. The plane was to be powered by new de Havilland Ghost engines (flown first in 1945, with thrust of 22.25 kN), and as Brabazon argued, "its appearance ahead of any rivals would be a timely reminder of the pioneering work done on jet propulsion in this country" (Nahum 2004, 142).

The Comet's first test flight took place on the evening of July 27, 1949. In October, it made its first long-distance flight to Libya and back, and the first passenger service began on May 2, 1952, with the BOAC flight from London to Johannesburg (Cowell 1976; [fig. 4.9](#)). In the same year, BOAC added routes to Ceylon and Singapore and in April 1953 to Tokyo. Compared to the latest generation of jetliners, the Comet was a plane with many drawbacks. With high fuel consumption (7,500 L/h for Comet 1) and with only thirty-six passengers on board, it was not a profitable way to fly. Because the cabin was pressurized only to the equivalent of nearly 2.5 km above the sea level, it was not very comfortable, and because the maximum range of Comet 1 was just 2,414 km (raised to 2,850 km for Comet 1A), it had to make several refueling stops on all long-range flights.



**Figure 4.9**

A de Havilland Comet (in Royal Air Force service) with four Ghost turbojets in flight.



Photo courtesy of the Royal Air Force.

More seriously, the Ghost Mk1 engines had a low thrust (22.3 kN) and a very low thrust-to-weight ratio of just 0.17 (2.5 to 3 percent of today's ratios), and this made the airplane prone to excessive rotation and a loss of acceleration during takeoff. In addition, the placement of its engines close to the cabin (in the wing roots next to the fuselage) led to concerns about the consequences of engine disintegration. Less than six months after the Comet began its scheduled service, a plane did not gain altitude on its takeoff in Rome, overshot the runway, and broke its landing gear. There were no fatalities, but a similar takeoff accident took place on March 3, 1953, when a plane on a delivery flight to Sydney (where it was to commence its service for Canadian Pacific) crashed in Karachi, killing eleven people. Both accidents were first attributed to pilot errors, but investigations uncovered a common technical cause—a loss of lift that was addressed by redesigning the plane's wings.

Just two months later, another Comet disintegrated as it flew into a severe tropical thunderstorm just after a takeoff from Calcutta on its way to London. This crash was traced to an overloaded tail section, and on May 2, 1953, yet another plane broke its landing gear as it overshot the runway in Dakar. But deficiencies and higher risks were to be expected with the first commercial application of a new prime mover whose military applications at that time were not even a decade old and whose working prototypes did not even exist fifteen years before the Comet first took off. At 640 km/h the planes were twice as fast as the fastest commercial propeller airplanes in service at that time, and there were well-justified hopes for rapid technical improvements in engine, fuselage, and avionics design.

But the Comet's prospects ended just twenty months after a small fleet of new planes began flying. A BOAC plane that had just taken off from Rome on its way to London fell into the Mediterranean near the island of Elba on January 10, 1954, causing thirty-five deaths. And on April 8, 1954, a plane leased to South African Airways met the same fate: after taking off from Rome, it fell into the sea near the island of Stromboli (Darling 2005). After five out of nine Comet 1 airplanes ended in crashes, all of the remaining Comets were grounded, and a two-year investigation eventually exonerated the engines and traced the failures to metal fatigue and ensuing rupture of the pressurized fuselage. Deterioration began with tiny stress cracks around

the plane's square window frames and led to a rapid decompression (catastrophic rupture) of the fuselage.

The world's second (and now nearly forgotten) jetliner (and the first gas-turbinepowered transport plane to land in many large U.S. cities) was a Canadian design (Arrow Recovery Canada 2009). The Avro Canada C102 made its first flight on August 14, 1949, just two weeks after the Comet's takeoff, but it never got beyond a prototype stage and a number of demonstration flights from Toronto and between the U.S. cities in 1950. In 1951, the company was ordered by the Canadian government to stop working on civilian designs and concentrate on military jets (Mellberg 2003). And so the failed Comet remained the only commercial jetliner of the early 1950s, and by the time its completely redesigned version—the Comet 4 with RollsRoyce Avon engines—was put into scheduled operation in October 1958, other jetliners were either already in regular service or just about to begin their commercial flights.

A prototype of the Boeing 707 first flew on July 15, 1954, the prototype of French Caravelle first flew on May 27, 1955, and the Soviet Tupolev Tu-104 was first tested on June 17, 1955. The Tu-104 was revealed at the Zurich air show in May 1956 and entered regular service on the Moscow, Omsk, Irkutsk route on September 15, 1956. The plane was essentially the Tu-16 strategic bomber (code-named Badger by the North Atlantic Treaty Organization), with a larger main fuselage. Its obvious military origins extended to two braking parachutes that slowed down the plane on landing because it had no thrust reversers (and also no noise suppression). Its two Mikulin RD-3 turbojets were, as in the Comet, buried in the wing roots, but they were much more powerful, with a thrust of 66.2 kN. French Sud Aviation's Caravelle entered service in 1959.

But neither the French (whose plane initially used Rolls-Royce engines) nor the Russians (whose gas-turbine designs were based to a large extent on Rolls-Royce's Nene engine) were a threat to the British lead in turbojet design. And neither de Havilland's nor Mikulin's pioneering turbojet designs were the greatest beneficiaries of this great transition as they did not provide the beginnings of lasting aeroengine dynasties. British primacy in jet engine design was lost to American gas-turbine makers, who had a clear technical lead by the time the new Comet 4 entered service, but Rolls-Royce was eventually able to join Pratt & Whitney and General Electric to make a lasting trio.

Pratt & Whitney's J57 turbojet, tested for the first time in 1950, marked a clear departure in gas-turbine design. This was the first twin-spool engine with a low-pressure compressor connected to a low-pressure turbine by a shaft rotating inside a second shaft that connected the high-pressure compressor and a high-pressure turbine placed aft (Heppenheimer 1995). This arrangement brought a much higher pressure ratio, and it increased thrust (this was the first engine to reach 10,000 pounds, or 44.4 kN, of thrust), overall efficiency (and hence lower fuel consumption), and engine performance during acceleration and deceleration. The new engine was used first on the Boeing B-52, America's enduring long-distance strategic bomber. Boeing won the competition to build the plane in 1948, and the bomber began to fly in 1955. It has remained in service into the twenty-first century as the only warplane that has been flown by three generations of crews.

The engine's commercial version, known as the JT3, was chosen to power America's first passenger jetliner, the Boeing 707. The airliner itself was based on an earlier long-distance bomber, the B-47, which introduced two lasting design features that were present in all large jet aircraft during the remainder of the twentieth century—35-degree swept-back wings and pod engines hung on struts under the wings (Tegler 2000). Boeing announced its plans to build a commercial jetliner on September 2, 1952, but the prototype tested in July 1954 was designed to serve both as a flight-refueling tanker and a freight carrier (and a later version became the first Air Force One, the presidential jet).

The first passenger version was the Boeing 707-120, which had four Pratt & Whitney JT3D turbojets, each with a thrust of 84 kN (roughly four times that of the de Havilland Ghost) and with a thrust-to-weight ratio of 3.5 to 4.0. This version inaugurated Pan Am's trans-Atlantic jet service on October 26, 1958, with a New York to Paris flight, and domestic flights commenced with American Airlines in January 1959 (Boeing 2009a; [fig. 4.10](#)). On October 10, 1959, Pan Am began to use the plane for its famous around-the-world service (Mellberg 2003). Eventually, the west-bound PanAm 1 flight connected Los Angeles with Tokyo, Hong Kong, New Delhi, Karachi, Frankfurt, London, and New York, with an alternative route from Hong Kong to Frankfurt via Bangkok and Bombay. Different versions of the plane (the last one was built in 1991) carried between 141 and 179

passengers, and its indisputable commercial success laid a solid foundation for a continuing series of Boeing's jetliners (see [chapters 5 and 6](#)).

The Boeing 707 was soon followed by the midrange Boeing 727 (in regular service beginning in February 1964 and produced until 1984) and the short- to midrange Boeing 737. This baby of the Boeing family was flown first in 1968 and has become the best-selling jetliner in history. By 2008, orders for the 737 surpassed six thousand (more than the orders for all of Airbus's planes), and its latest versions—the 737-900, the 737-900ER (introduced in 2006), and their progeny—will be selling for decades to come (Boeing 2009b). The Boeing 707 was soon joined by the DC-8 (McDonnell Douglas first flew this on May 30, 1958, and it has been in service since September 1959), the Convair 880 (a midrange jetliner that was first flown on January 27, 1959), and the Convair 990 (its first flight was on January 24, 1961).



**Figure 4.10**

Pan American's Boeing 707, a turbojet-powered foundation of the Boeing family of jetliners. Photograph from author's collection.

Hundreds of these planes were ordered by scores of customers during the late 1950s and the early 1960s as airlines on all continents rapidly switched from piston aircraft to first-generation jetliners on all long-distance routes, and General Electric's aeroengine division became one of the major beneficiaries of this great prime-mover transition. General Electric's history of jet-engine manufacture began (as already explained) by replicating

Whittle's design. Its 1-A engine ran for the first time in April 18, 1942, and in October 1, 1942, a Bell XP-59A Airacomet with a GE I-16 turbojet (5.55 kN) made America's first jet-powered flight (General Electric 1979). By 1944, the J33 (I-40) reached 17.8 kN, and in 1947, it set a new world speed record of 998 km/h.

The company continued to concentrate on military engines—first (during the late 1940s and the early 1950s) with its successful J47, which was initially intended for the F-86 Sabre and which eventually became the most widely produced gas turbine with more than 35,000 units sold before the end of the 1950s. In 1952, General Electric introduced its J79, which remained in production (with more than seventeen thousand units) for more than thirty years and powered jets for Starfighters and Phantoms. Its commercial derivative, the CJ805, was GE's first entry into jetliner market. In 1961, it was chosen to power the Convair 990, at that time the plane with the fastest design speed (Mach 0.89 compared to the most common Mach 0.85) (Kutney 2007).

General Electric's 1965 high-bypass turbofan—the TF39 for the giant C-5 Galaxy military transport airplane—became the basis for a very successful CF-6 commercial engine, which was used first by the DC-10 in 1971 and later by the Boeing 747 and 767 and the Airbus 300, 310, and MD-11. In 1974, General Electric and France's Snecma Moteurs established a joint company—CFM International. Its name was derived from the designation of two well-known engines produced by the companies—General Electric's CF-6 and Snecma's M56—and the company has specialized in making engines for short- and medium-range aircraft, such as successive variants of the Boeing 737 and Airbus models 318 to 321 (CFM 2009).

Rolls-Royce was the best-positioned gas-turbine maker to enter the postwar commercial market thanks to its initial development lead (converting Whittle's design into a serially produced Welland engine in the Gloster Meteor by 1944) and to the subsequent development of more powerful engines for military uses (the Nene and the Derwent). Its first commercial engine was the Dart in the turbo-prop Vickers Viscount, but its first commercial turbojet, the Avon (which was introduced in 1950 and built until 1974), was used initially by only the redesigned Comet (since 1958) and the French Caravelle SE 210, an eighty-seat plane that was designed by Sud Aviation (later Aérospatiale) for connecting France with North Africa

and that entered regular service four years after its first prototype flight, on May 12, 1959. It was the first jetliner with two rear-mounted Avon RA-29 units rated at 46.7 kN (later it also used Pratt & Whitney's JT8D9).

The Conway—Rolls-Royce's and the world's first turbofan engine (more details on these engines follow in the next section)—was used on the VC10, B-707, and DC-8 before it was displaced by the JT3D. Rolls-Royce's next bold goal was the RB211 for wide-body airliners, but its excessively costly development bankrupted the company and led to its nationalization in February 1971. The engine was the first design to have a triple-spool arrangement (a wide-chord fan, a seven-stage intermediate- and six-stage high-pressure compressor, a single-stage high- and intermediate-pressure turbine, and a three-stage low-pressure turbine) and carbon fibers used for rotor blades. It was completed by the nationalized company more than a year later than originally scheduled and entered service in April 1972 on the Lockheed L-1011 (Tri-Star) and DC-10. It was later used on the Boeing 747 and 757. Early versions of the RB211 produced 187 kN, and by 1977, its rating rose to 222 kN.

By the early 1970s, just two decades after the (aborted) launch of commercial jet aviation, the world market for gas turbines to power the world's fast-growing fleet of commercial aircraft was thus competitively supplied by three experienced engine makers whose turbojet prototypes were based on Whittle's W.1. Remarkably, at the beginning of the twenty-first century, these three companies still dominate the global market for jet engines. And by the early 1970s, these three companies had also completed an important transition from turbojet to turbofan engines, whose concept dates back to the pioneering decade of British jet propulsion (Coalson 2003).

## **The Beginnings of the Turbofan Era**

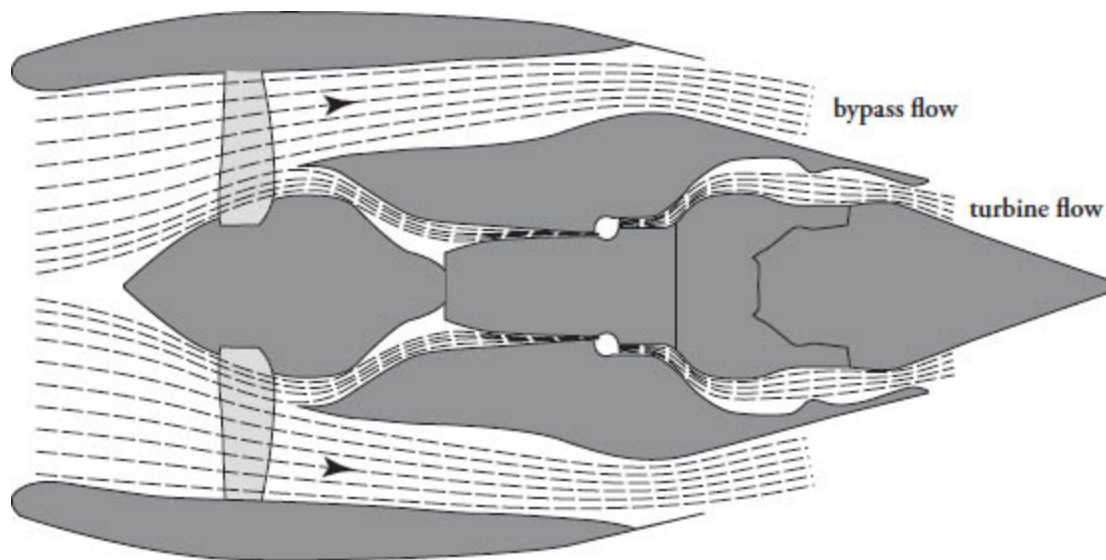
Turbojets based on military designs were not the most suitable engines for large passenger planes, which is why they were rather rapidly replaced by more powerful and more efficient turbofan engines, whose conceptual design goes back to the work of Alan Griffith and Frank Whittle in the 1930s. The principal reason for the higher efficiency of turbofans can be explained with the help of basic Newtonian physics. Because thrust is a function of jet velocity while the kinetic energy increase is a function of the

square of jet velocity, the higher thrusts generated by faster jets will result in lower propulsion efficiencies.

Such an unwelcome trade-off is acceptable for fighter planes that are designed for superior combat performance (reaching supersonic speeds and using high thrust to generate high rate of climb) and whose relatively low propulsion efficiency and high fuel demand can be (expensively) compensated by airborne refueling on longerlasting missions. In contrast, fuel cost is a major component of the overall operating cost of commercial aviation, and hence the quest for higher propulsion efficiency (and resulting lower jet fuel consumption) must preoccupy all designers of passenger jets. Whittle sought to resolve this challenge long before he built the first working prototype of his turbojet.

This is how he summarized his quest decades later (Golley and Whittle 1987, 262-263):

From the earliest days of my work on the jet engine I realised that for speeds of the order of 500 mph the propulsive efficiency would be only about 50% as compared to about 80% for a propeller at much lower speeds, so I cast around for ways to improve on this; I wanted to “gear down the jet,” i.e., to convert a low-mass high-velocity jet into a high-mass low-velocity jet. The obvious way to do this was to use an additional turbine to extract energy from the jet and use this energy to drive a low pressure compressor or fan capable of “breathing” far more air than the jet engine itself and forcing this additional air as “cold jet.”



**Figure 4.11**  
Schematic cross-sections of a turbofan engine.

In formal terms, the force ( $F$ ) generated by a gas turbine is a product of the mass flow rate of the air ( $m$ ) and the difference between relative speeds of air entering ( $V_i$ ) and leaving ( $V_e$ ) the engine:  $F = m(V_e - V_i)$ , while the propulsive efficiency ( $\eta$ ) of a turbine is  $\eta = 2 V_i / V_i + V_e$ . Because  $V_i$  is obviously equal to the forward speed of the aircraft and must be maintained at the desired cruising rate, the only practical way to improve propulsive efficiency is to reduce the speed of the exiting jet stream—but, as shown in the first equation, such a reduction will lower the thrust unless there is an increase in mass air flow. This is precisely what a turbofan accomplishes. It operates with a greater mass of air than a turbojet, and most of that air bypasses the engine's core and exits the nozzle at a speed lower than the air that passes through the engine's combustor (fig. 4.11). The difference in air speeds is roughly twofold: while the hot air from turbojet exits through the nozzle at nearly 900 m/s in turbofans the bypassed air moves at around 450 m/s. Turbofans extract more power from the gas in the turbine to compress more air by an additional set of large-diameter fans placed ahead of the compressor. These fans compress the incoming air to usually less than twice the inlet pressure, and this air then bypasses the combustion chamber, thereby obviating the need for more fuel and resulting in lower specific fuel consumption. The greater mass of these two streams of exhaust gases (the rapid one from the core and the slower bypass flow) generates higher thrust.

No less important is the fact that the thrust peaks in turbojets at the very high speeds that are needed for fighter planes, but in turbofans it is highest during low speeds, which makes them particularly suitable for large planes that need extraordinary power during takeoff. After all, a fully loaded Boeing 747 weighs nearly 400 t, and the maximum takeoff weight of an A 380 is 560 t. Even those travelers who were completely unaware of this great technical improvement could feel its results as takeoffs became much less nerve-wracking. While the turbojet-powered Boeing 707-120 took up to forty-five seconds to leave the runway, the first turbofans cut the takeoff time to twenty-five to thirty seconds, and the much more powerful engines of the 1990s and the first decade of the twenty-first century can make commercial jets airborne in less than twenty seconds. Turbofans are also considerably quieter than turbojets because the high-speed, high-pitched exhaust from the engine's core is enveloped by slower and much more voluminous bypass air.



Bypass ratio is calculated simply by dividing the mass of air that flows outside the engine core by the mass of air that moves through the turbine, and there are limits to the benefits arising from its increase. Because of higher propulsion efficiency, specific fuel consumption decreases as the bypass ratio increases, but the rate of this decline diminishes. Increasing the bypass ratio from 1 to 4 improves the specific fuel consumption by nearly a third, but raising it from 4 to 8 brings only an additional 10 percent gain. Moreover, with a rising bypass ratio, the engine gets both heavier and larger. This additional mass and increased nacelle (engine's cover) drag mean reduced thrust and higher specific fuel consumption. Even more important, a much larger engine would require the wings to be positioned higher off the ground, a change that would affect the aerodynamics of the entire aircraft and would require a longer and heavier undercarriage, which would further affect fuel consumption (and would mean that it could not fit into existing airport slots).

Experience with high-bypass engines shows a predictable tradeoff. Marginal specific fuel consumption decreases are more than negated by the fact that an aircraft with lighter lower-bypass engines can carry more payload or travel farther with the same amount of fuel. There is a broad consensus that bypass ratios in excess of 8 to 1 are incompatible with minimizing overall fuel consumption. However, high-bypass engines generate much less noise, an important consideration in operating modern aircraft in congested airports where takeoff and approach paths affect densely populated areas. The eventual choice of bypass ratio should be guided by a quest for not the most efficient engine but one whose operation will be most profitable or most acceptable for the airline. Because the higher entry temperatures and pressures of modern engines produce more power from the same air-mass flow, the bypass ratio alone has become a rather flawed descriptor of an engine's performance, and specific thrust (net thrust per unit of mass flow through the engine) is a better choice (Cumpsty 2003).

The most obvious practical challenge in designing a large turbofan (with a bypass ratio of greater than 3 to 1) is the construction of fan blades. Because of their large radius (a maximum of 1.25 to 1.5 m) and the high revolutions per minute, their speeds of around Mach 1.5 at their tips make most of the blade supersonic and hence require materials of extraordinary durability that are machined with great precision. Early designs had no

choice but to use solid metal (titanium), but such long, narrow blades were aerodynamically unstable and were subject to vibration (flutter) that could lead to their disintegration. To prevent this flutter, both sides of a blade were fitted with blunt projections called *shrouds*, *snubbers*, or *clappers*, which were placed about two-thirds of the distance from the blade's root. These rubbed against their neighboring shrouds and dampened any flutter. As already noted, Rolls-Royce's first attempt to build the blades from Hyfil, a carbon-composite material that was laminated with resins, ended in failure, and the company succeeded in commercializing the first lightweight blade—which was wide yet hollow and shroudless—only in 1983. Even more remarkable blade designs were introduced later by General Electric (see the next chapter).

Milestones on the road to high-bypass engines are much easier to recount than the more complicated early development of turbojets. Whittle patented his bypass idea in March 1936 (he called the arrangement a *thrust augmentor*), and in 1943, when he was at the Royal Air Force Staff College, he actually designed a turbofan engine (27 kN, with ten axial compressors and one centrifugal compressor) to power long-range bombers that were able to reach Japan from the British India. But just before the prototype of LR.1 was to be tested in the spring of 1944, the nationalization of Power Jets ended its development (Gunston 2006). The turbofan concept thus could be converted into reality only after the turbojet design itself passed from its pioneering stage to a mature era after World War II. Rolls-Royce was the first aeroengine maker to introduce a commercial turbofan with its low-bypass Conway engine, which was tested for the first time in July 1952 at 44 kN of thrust. Its bypass ratio was merely 0.3 to 1, and its larger versions were used on a number of airplanes in the late 1950s.

Most important, this engine served as a model for Pratt & Whitney as it added bypass to its JT3 and created the JT3D engine with 80.1 kN of thrust and a bypass ratio of 1.4 to 1. The engine was used first in 1959 and then installed in the Boeing 707, Boeing 720, and Douglas DC-8. Pratt & Whitney eventually produced more than 21,000 J57/JT3 engines, ending their run only in the 1980s. All subsequent gas turbines for large passenger airplanes have been turbofans with steadily increasing bypass ratios and higher thrust. The highest bypass ratios in the early 1960s did not surpass 1.7 to 1 and were mostly below 1.5 to 1—and then came Pratt & Whitney's

revolutionary JT9D, the first high-bypass ratio engine for wide-body jetliners (Pratt & Whitney 2009a; [fig. 4.12](#)).



**Figure 4.12**

Pratt & Whitney's JT9D, the first high-bypass-ratio engine for wide-body jetliners, was the launch prime mover for the Boeing 747.

Photograph and the engine section available at the Pratt & Whitney Web site.

The development of the JT9D began in September 1965, and it was first tested in December 1966, certified in May 1969, and entered commercial service in January 1970 (Pratt & Whitney 2009a). This massive engine (with a fan-tip diameter of about 2.35 m and a dry weight of 4 t) had a bypass ratio of 4.8 to 1, a fan-pressure ratio of 1.67 to 1, and an overall pressure ratio of 26.7. The engine had a maximum takeoff thrust of 210 kN (later versions were upgraded to as much as 249 kN), and it was the first giant turbofan with double-shrouded (narrow and long) blades (Sample and

Shank 1985). The engine was introduced to power the world's first wide-bodied airplane—the Boeing 747 with four JTDs under its wings—and by the time its production ended in 1990 (an enhanced version JT9D-7R4 was introduced in 1982), more than three thousand units had been sold to propel entire fleets of the Boeing 747, twin-engine Boeing 767, Airbus 300, Airbus 310, and triple-engine DC-10.

General Electric's first entry into turbofans was with the CJ-805, an unusual aft-fan engine (the fan was mounted with and behind the turbine) that was tested in 1957, and by 1964, the company had built a demonstrator engine with a bypass ratio of 8 to 1—an extraordinary advance, considering the fact that other contemporary designs considered a bypass ratio of 3.5 to 1 as the limit (Coalson 2003). General Electric's commercial offering of this turbofan, the TF39, was, as already noted, the foundation of a highly profitable family of CF-6 commercial engines that were used for the first time in the DC-10 in 1971 and later in Boeings and Airbuses. By the early 1970s, another era in the short evolution of jet engines was thus firmly underway as high-bypass-ratio engines became not just the dominant but the only choice for all aircraft flying long distances at high subsonic speeds (typically at Mach 0.85 to 0.9).

# 5

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## Two Prime Movers of Globalization

Es ist schön, so zu gestalten und zu erfinden, wie ein Künstler gestaltet und erfindet. Aber ob die ganze Sache ein Zweck gehabt hat, ob die Menschen dadurch glücklicher geworden sind, das vermag ich heute nicht mehr zu entscheiden.

[It is wonderful to design and invent in the way that an artist designs and creates. But whether it all has a purpose, whether people have become happier as a result, that I can today no longer decide.]

—Rudolf Diesel

Technical advances can be driven overwhelmingly by a singular preoccupation (such as maximized efficiency, increased overall power of an operation, or minimized environmental impacts) or by a combination of goals. The first instance (as the following examples show) is not uncommon. Improved efficiency has been the main aim for designers of the ever larger steam turbogenerators that now produce the bulk of the world's electricity. Typical efficiencies of thermal electricity generation rose from just around 5 percent in 1900 to just over 20 percent by 1950 and about 35 percent by the beginning of the twenty-first century (Smil 2005). The quest for higher computing power, best exemplified by Moore's law (see [fig. 3.1](#)), has preoccupied microchip designers since the initial commercialization of the devices in the late 1960s (Smil 2006). After just three decades of development, better catalytic converters reduced nitrogen oxide emissions from passenger cars in the United States by 95 percent compared to precontrol (1971) levels. They also cut carbon monoxide emissions by 96 percent and hydrocarbon releases by 99 percent (Motor Vehicle Manufacturers Assn. 2000).

But even in those cases where a major goal is clearly identifiable, there are other considerations at play, and most technical advances have been driven by a combination of aspirations and aims. Some of these combinations have included goals that are clearly conjoined and complementary (higher efficiencies and greater reliabilities will generally

mean lower operating costs), and others have aims that lead in opposite directions (increased travel speeds will lower fuel efficiency and increase operating costs) and whose partial achievement calls for compromise designs. Continuing improvements of diesel engines and gas turbines have shared a number of common aims—quests for higher efficiency, lower operating costs, greater reliability, and lowered environmental impact—but many specific goals and innovations are applicable only to particular commercial niches or functions.

For example, during the past four decades of commercial jet flight, there have been only some relatively small changes in the formulation of jet fuel (different types of kerosene). But the development of marine diesel engines has aimed at broadening the variety of fuels that can be used by these powerful machines. Many of them can now burn heavy fuel oil and natural gas in addition to standard diesel fuel. And while the increased reliability of operation is always a desirable goal, this quest is literally a matter of life and death for the jet engines that power the wide-body aircraft that carry hundreds of passengers. A malfunctioning diesel engine on a cargo ship will delay an intercontinental delivery of some (often superfluous) manufactured goods from Asia, but a failed blade in a large turbofan could bring down a jetliner. Fortunately, such failures have become exceedingly unlikely as constant improvements have made the turbines that now power the latest generation of commercial jets (those introduced during the 1990s—the Boeing 777 and Airbus 340) much more reliable than were those used during the pioneering decade of the 1950s.

Looking back at the post-1950 advances in the design and operation of diesel engines and gas turbines, it is difficult to say which one impresses more. By the early 1950s—when Western countries and Japan had largely regained their prewar economic levels and were ready to embark on a new period of growth—the design and production of diesel engines were mature enterprises. There were to be no radical changes in the basic mechanism and overall configuration of large machines (built as multicylinder in-line assemblies with massive pistons), and there was no prospect of any major performance gains. In 1950, MAN's supercharged four-stroke engine was the first internal-combustion machine to reach the 45 percent efficiency mark. In contrast, in the early 1950s, the use of jet engines in commercial aircraft was at its very beginning (in a stage akin to that of diesel-engine applications in the last pre-World War I decade), and it was not at all clear

how rapidly the new jet-powered airlines would grow and what demands for new engine designs (and their eventual mass manufacturing) they would create.

Not surprisingly, large commercial jet engines have become more fuel-efficient and have undergone a major redesign as turbofans replaced turbojets. The latest generation of large turbofans that powers wide-body jets on intercontinental flights (many lasting more than twelve hours) undoubtedly represents the most complex and yet most reliable large machines in widespread use. Diesels have seen relatively small but cumulatively important gains in efficiency and reliability and, above all, a rather spectacular growth of the largest cylinder and machine capacities (the largest twelve- to fourteen-cylinder marine diesels now rate close to 100 MW) combined with a no less impressive growth in the total numbers and aggregate ratings of new engine sales. In addition, their combination of reliability (even when operating in extreme environments), durability, efficiency, flexibility, and low operating cost has made them absolutely indispensable for the functioning of modern civilization.

They are more important than are jet engines for the global economy and not only because they power virtually all intercontinental shipments of all goods. They also power most of the bulk transport on roads, rails, and waterways. Less visibly but no less important, they contribute to the global economy by energizing tasks including road building, oil and gas exploration, electricity generation, and mechanized crop harvests. But gas turbines have found other important uses besides air transport, whether for energizing compressors that are used in oil and gas pipelines or for generating electricity more efficiently (in combined cycles with steam turbines) than any other primary fuel convertor. That is why—after two sections devoted to reviews of technical accomplishments and innovative advances in design, manufacturing, and deployment of the two classes of machines that have made the current extent of economic globalization possible (large marine diesels that power intercontinental shipping and turbofan jet engines used in long-distance flights)—I offer a closer look at other important roles that these diesels and gas turbines have come to play in the global economy.

## **Diesels in Marine Transportation**

The global economy transports raw materials and manufactured products on a scale that was not easily imaginable even as recently as the middle of the twentieth century. At that time, there were no supertankers bringing oil from the Middle East to Japan, Europe, and North America; no enormous bulk carriers carrying iron ore or coal from Brazil and Australia to China; and both the container vessel and the liquefied natural gas tanker were yet to be invented. The radical changes of all of these realities were made possible by developing more powerful, more efficient, more reliable, and less polluting diesel engines whose advanced designs have been tailored to the specific requirements of particular uses and markets. The emergence of a true planetary economy would have been impossible without inexpensive intercontinental marine transport, and this industry could not have reached its current magnitude and intensity without prime movers that combined all of those desirable attributes. Marine diesel engines have provided this essential service, and this section is devoted to their recent development, production, and performance.

Although (as is explained in [chapter 3](#)) diesels began their conquest of commercial shipping even before World War I and gained about a quarter of that market by 1939, it was not until the 1950s that diesels conquered the industry, displacing venerable steam engines and much-better-performing modern steam turbines alike. The economies of the switch were decisive. Tanaka (1958) compared a 15,000-hp steam turbine and an equal-sized diesel (a MAN B & W Diesel design with turbo-chargers) that was used by a typical newly built Japanese oil tanker of 33,000 dwt and found that the increased investment in the diesel would be repaid by higher operating profits within two years. By the late 1960s, steam engines had virtually disappeared, and steam turbines were retained only in some specialized niches. The conquest of shipping by diesels was complete.

Modern marine diesels are now tailored to three specific markets. The world's most powerful diesel engines are invariably two-stroke machines that operate at low speeds and that were developed principally for the very large crude carriers (VLCC), ultra-large crude carriers (ULCC), bulk carriers, and container ships in which they drive their single propellers ([fig. 5.1](#)). Two-stroke machines for the largest vessels are preferred for several reasons. Because their power stroke takes place at every down stroke, the two-stroke machines are nearly twice (the actual ratio is about 1.8) as powerful as a four-stroke engine of similar mass. Their simpler construction



(no intake valves) lowers the chance of operating problems, their slow speeds (typical speeds come in clusters of 76 to 79 rpm, 91 to 97 rpm, and 102 to 108 rpm) make it possible to burn heavy fuel oil efficiently, and, perhaps most important, their slow speed allows a direct coupling between the crankshaft and the propeller shaft, eliminating any transmission gear and hence reducing the engine's overall mass-to-power ratio.

During the upward stroke (with the crankshaft revolving clockwise), the rising piston compresses the air above 1 MPa, and the temperature surpasses 500°C. Fuel is injected just before the piston reaches the top dead center (TDC), and the expanding combustion forces the piston downward and rotates the crankshaft. The exhaust valve opens at about 110 degrees past the top dead center, and scavenge ports open immediately afterward (at about 140 degrees past top dead center) to admit pressurized air and clear out the remaining exhaust gas from the cylinder. The piston passes the bottom dead center and moves up, and after it closes off scavenging ports and the exhaust valve, a new compression phase begins.



**Figure 5.1**

The MAN Diesel 12K98MC, a powerful two-stroke marine diesel engine (the first diesel rated at more than 100,000 brake horsepower) that is designed to propel large, fast container ships. This shows the engine's testing at Hyundai Heavy Industries in 2006.

Photograph available at the MAN Diesel Web site.

Perhaps the most remarkable attribute of these massive engines is that they experience surprisingly low diametrical cylinder liner wear (on the

order of just 0.03 mm/1,000 hours of operation) despite their enormous power output and large stroke length. This is made possible by the fact that the top of the connecting rod is attached not directly to the piston but to a crosshead that rides in guide channels and that is attached to the piston by a long piston rod. This arrangement minimizes the sideways forces that are produced by the connecting rod in standard engines, whose cylinders gradually become oval-shaped.

Many types of merchant ships, specialized vessels (including tugs and ships used for the dredging and laying of submarine cables), and passenger liners are powered by four-stroke medium- and high-speed diesels. Their required ratings are obtained by using the most suitable multiengine configurations. Finally, all of these vessels have a common need to generate electricity onboard, a task that is best done by multicylinder four-stroke diesels of various capacities, most commonly ranging from a few hundred kW to less than 5 MW. For the sake of economy and ease of installation, these generation sets burn the same fuel as the ship's main engines.

Before taking a closer look at the main engine markets (and a few specific engines), a few paragraphs on general matters of marine propulsion are in order. The power that is needed to propel a ship must overcome three main sources of resistance—the frictional resistance of the hull, which is dependent on the hull's wetted area and which rises with the square of the ship's velocity; the residual resistance that is due to the waves and eddies created, respectively, by the ship's movement through water and to flow separation; and air resistance that is proportional to the ship's cross-sectional area above the waterline and rising with the square of the ship's speed (Harvald 1991; MAN Diesel 2006a). The relative importance of these factors varies with ship design, speed, and environmental factors. Frictional resistance dominates in large, low-speed vessels (amounting to 70 to 90 percent of the total), residual resistance contributes up to 25 percent, and air resistance accounts for the small rest. However, in high-speed ships, the frictional and wave and eddy resistance may be nearly equal.

Several factors modify these generic realities. The power that is needed in head-on seas may be as much as twice as high as in calm weather, and extreme values on such rough routes as Japan to Canada may reach 220 percent. Typical power markups (so-called sea margins) on the westward (against the prevailing wind) routes in the North Atlantic are 25 to 35 percent, and on most other frequently traveled routes they are between 20

and 25 percent. That is why engine designers add at least 15 percent to the minimum power of engines required to propel ships on calm seas. The size of the waves and ocean currents adds to and complicates these mark-ups. Resistance also begins to increase almost as soon as a ship is launched because of a continuous erosion of its smoothly painted surface and the growth of marine plants and barnacles on the hull. Over time, these changes may push up the total resistance by as much as 50 percent. Air resistance may account for as much as 10 percent of the total for the vertiginously loaded container vessels in a head wind.

An engine's power is converted to motion through propellers with two to six blades. Two-bladed propellers are the most efficient but are used only on small ships. Structural considerations require multibladed propellers on large vessels: four blades are used with slow two-stroke engines, but fast container ships with powerful engines have five or six blades. Freight ships that maintain steady speeds do not need the considerably more expensive controllable pitch propellers (which are used for ships that require a high degree of maneuverability) and use simpler and more reliable fixed-pitch propellers that are usually single castings made of a copper alloy. Propulsion efficiency increases with propeller diameter, but other considerations limit its size. Casting and production costs limit propeller diameters to 10 to 11 m and this corresponds to maximum engine power ratings of 90 MW. Moreover, large tankers and other massive bulk cargo carriers usually make one journey in ballast condition, and this limits the size of the propeller because it should remain fully immersed even when the ship is not loaded.

For ships requiring power of more than 100 MW the best solution would be to have two main engines and two propellers. So far, however, the growth of engine capacities has sufficed to provide all the requirements presented by the growth of all three major categories of long-distance ocean shipping whose rapid growth began during the 1950s—wet bulk carriers (including crude-oil tankers and ships transporting refined-oil products—mostly gasoline, diesel fuel, and fuel oil), dry bulk carriers, and container ships. The most recent addition to these distinct modes of intercontinental transport has been the export of natural gas by LNG tankers—bulk carriers with large, heavily insulated containers filled with gas cooled to  $-163^{\circ}\text{C}$  (fig. 5.2).

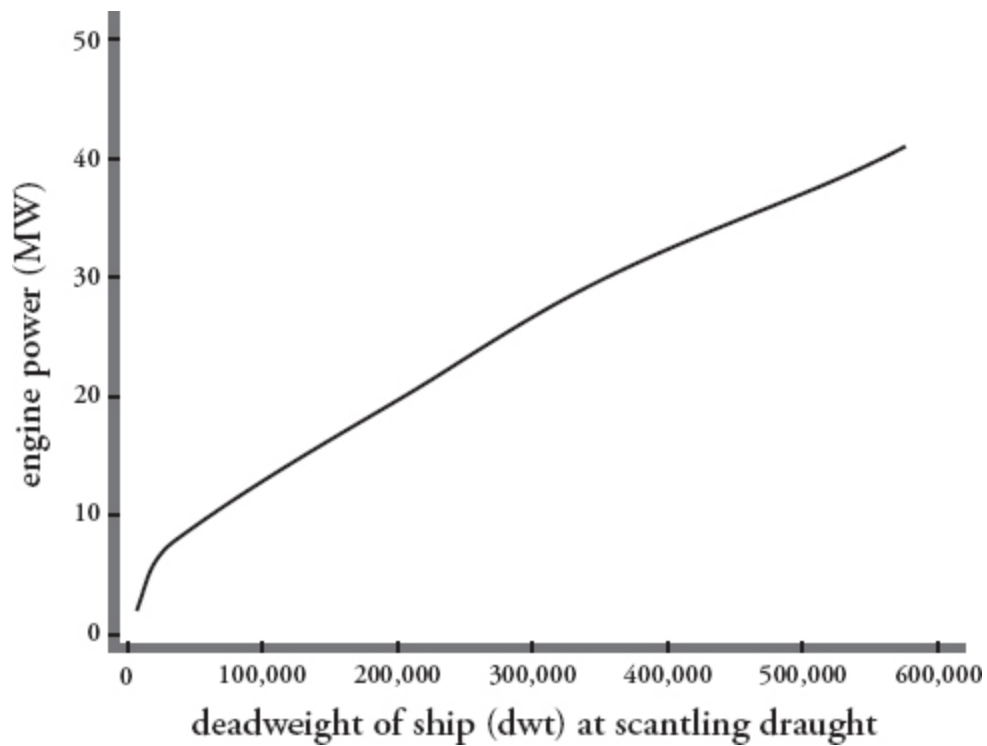
Tankers are classified according to their size, expressed in deadweight tons (dwt). This metric measure is the sum of a ship's carrying capacity and the bunkers (fuel and lubricants) that are needed for its propulsion. The maximum dwt for oil tankers is always specified for summer saltwater draft (that is, for the standard density of  $1.025 \text{ t/m}^3$ ). Small tankers used for local and coastal trade in refined products are less than 10,000 dwt. The handysize category (also mostly for products and chemicals) includes ships between 10,000 and 30,000 dwt, and Handymax vessels (typically for refined products) go up to 55,000 dwt. These three categories now make up nearly two-thirds of the world's tanker fleet of nearly 5,500 ships larger than 5,000 dwt but less than a quarter of total dwt (MAN Diesel 2007b).

Panamax ships (60,000 to 75,000 dwt, mostly crude-oil carriers) have a maximum breadth of 32.2 m and a maximum length of 289.6 m to fit the lock chambers that are 33.5 m wide and 305 m long (and that are now being enlarged). Aframax vessels (a term derived from the acronym for the American Freight Rate Association) are mostly crude-oil tankers of up to 120,000 dwt, as are Suezmax tankers with up to 170,000 dwt (as long as they are not wider than 70 m and have maximum draft of 21.3 m to move through the canal). VLCCs range from 250,000 to 320,000 dwt, and ULCCs surpass 350,000 dwt, and both are used only for crude-oil shipments. Aframax, Suezmax, and VLCC categories account for less than 30 percent of all ships but for about 70 percent of total dwt, with VLCCs alone claiming more than a third. The power needed to propel tankers is a function of their deadweight tonnage and their speed. The typical design speeds of modern tankers are 13.5 to 14 knots (25 to 26 km/h) for the smallest sizes, and 15 to 15.5 knots (roughly 28 to 29 km/h) for all larger vessels. Assuming actual engine performance at 90 percent of its specified capacity, engines rated at 2.5 to 3.5 MW suffice for the smallest ships, Handysize and Handymax categories need engines of 4 to 10 MW, for the next three classes the range goes from about 10 to 17 MW, and for VLCCs it is between 24 and 27 MW (MAN Diesel 2007b; [fig. 5.3](#)). The maximum continuous engine capacities needed for ULCCs are above 30 MW, and for vessels of more than 500,000 dwt, they would be around 40 MW for the design speed of 16 knots (29.6 km/h).



**Figure 5.2**

One of forty-five large liquefied natural gas tankers with insulated membrane tanks built for Qatargas and powered by a low-revolutions-per-minute, two-stroke MAN diesel. Photograph available at the MAN Diesel Web site.



**Figure 5.3**

The propulsion-power demand of oil tankers of different size categories (based on MAN Diesel 2007b).

Going faster or slower than a design speed makes a great difference. A 300,000-dwt VLCC traveling at its design speed of 15.5 knots (28.7 km per hour) needs 25.9 MW, going a knot faster pushes the need to about 32 MW, and going a knot slower reduces the power to roughly 21 MW. Regardless of ship size and speed, tanker engines are designed to run at very low speeds (54 to 79 rpm) to match the optimum propeller speeds. Many of them also use flexible settings (variable exhaust valve closure, load-dependent cooling, variable fuel injection timing) to accommodate extended periods of slow travel.

The rising power requirements of these ships have been met by building engines with a greater number of cylinders. All major producers offer six to twelve cylinders in-line machines that are over 10 m tall with cylinder bores approaching 1 m and with piston strokes exceeding 2.5 m. Wärtsilä's five- to nine-cylinder RT-flex84T and RTA84T (an original Sulzer design) with cylinder bore of 840 mm and piston stroke of 3.15 m and ratings up to 30 MW) have been a very popular choice for new VLCCs. The engines have been available in five to nine cylinders with overall ratings between 21 MW and 37.8 MW at 76 rpm and 16.85 MW and 30.33 MW at 61 rpm (Wärtsilä 2009b). MAN's most commonly used engines for VLCCs have been similarly sized machines of the MC and ME (electronically controlled) series, particularly the seven- and eight-cylinder S70 and S80 sets rated between about 16 MW and 33 MW (MAN Diesel 2008b).

Liquefied natural gas tankers were originally powered by steam turbines (with steam generated by burning the naturally boiled-off cargo gas), but most vessels are now equipped with diesel propulsion. Its two basic options are known as diesel low speed and reliquefaction (DLR) and dual-fuel diesel electric (DFDE). The first arrangement relies on low-speed diesels for propulsion and on several (four to five) auxiliary generation sets, whose output is used for operating cargo pumps, providing onboard electricity needs, reliquefying the natural boil-off gas, and feeding it back to the cargo tanks, with all engines burning heavy fuel oil. A modification of this concept includes high-pressure gas injection into the main low-speed engines. The second basic option uses four to five identical engines to drive the alternators and use the generated electricity to power all of the ship's

functions—propulsion motors, compressors, pumps, all auxiliary systems, and all accommodation needs. The dual-fuel engines can accommodate any ratio of natural boil-off gas to liquid fuel (either heavy fuel oil or marine diesel oil).

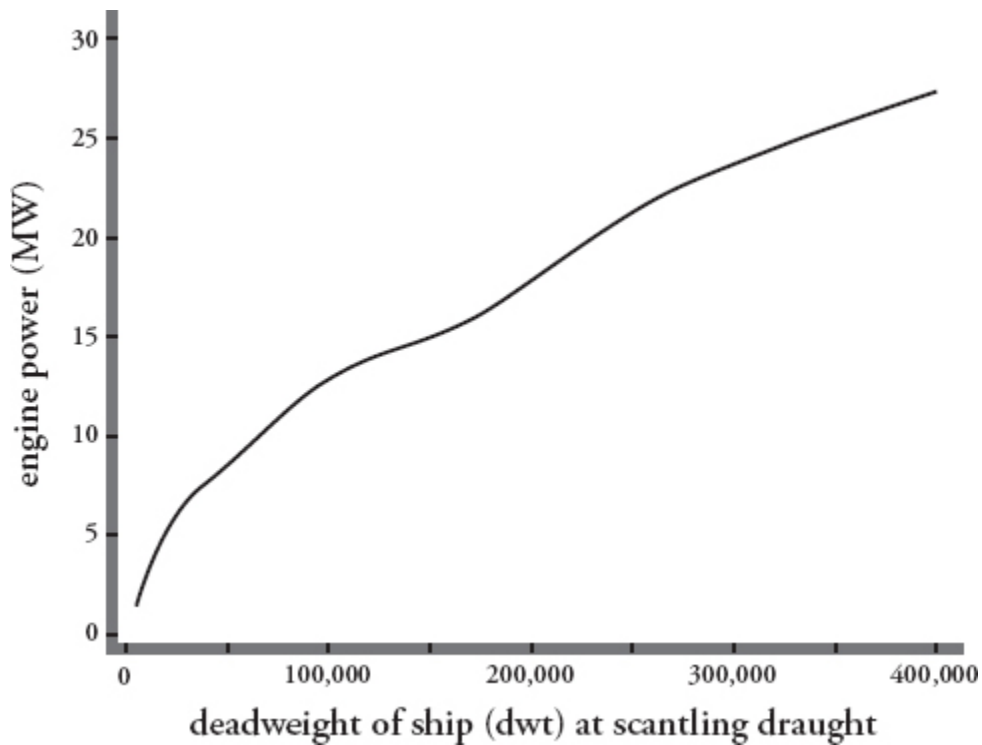
Boil-off rates in LNG tankers usually range between 0.11 and 0.15 percent of the load for every day of the ship's laden voyage. This means that a now standard-sized tanker with a carrying capacity of 155,000 m<sup>3</sup> could derive about 20 MW of mechanical energy from natural boil-off gas and about 10 MW during the ballast leg. Even the latter rate will be far in excess of the need during waiting to enter a terminal (1.5 MW), loading (4 MW), or discharging (7.5 MW), but it would not be enough to propel a fully loaded LNG tanker at its design speed of 18.5 to 20 knots (34 to 37 km/h) when, including the sea margin of 15 to 20 percent, 30 to 32 MW will be needed. More gas can be produced by forcing a greater rate of boil-off, but this option could deplete the cargo too much.

A MAN study of propulsion systems concluded that although a pure gas-burning option (using a gas turbine) could be preferable in some circumstances (especially with a high fuel oil to LNG price ratio), the dual option (burning natural boil-off gas and the usual diesel liquids) is the best choice for all very long transport distances and high LNG prices as it provides operational flexibility and minimizes overall fuel cost (MAN Diesel 2008b). The dual-fuel option using five engines also allows en route on-board maintenance, a necessary requirement for LNG tankers because they usually spend less than a day in a terminal. With five engines, it is possible to shut down one for maintenance while the other engines keep the load within allowable limits. Finally, compared to the less efficient gas-turbine operation, the dual option has the advantage of minimizing carbon dioxide emissions.

Dual-fuel operation is now also practiced as a useful innovation during the shipments of liquefied petroleum gas (LPG). With a major expansion of LNG (and, to a lesser extent, LPG) trade now underway and with advanced planning for transporting compressed (rather than liquefied) natural gas, there is no doubt that dual-fuel engines will become more common during the coming decades.

The power requirements of dry bulk carriers transporting coal, ores, or grain are very similar to those of crude-oil tankers of similar capacity, and so is the distribution of vessel sizes. The dry bulk fleet is dominated (more

than 70 percent) by vessels smaller than 55,000 dwt, with the Handysize category accounting for about a third of the total and the three largest categories—Panamax (60,000 to 80,000 dwt), Capesize (80,000 to 200,000 dwt), and very-large bulk carriers (VLBCs, with more than 200,000 dwt)—accounting for 60 percent of the fleet’s entire carrying capacity (MAN Diesel 2007a). The main difference is the typical design speed, as low as 12 knots (22 km/h) for the smallest bulkers and 14.5 knots (nearly 27 km/h) for all other vessels, with the exception of the largest Capesize and VLBC ships that travel just a bit faster than 27 km/h. These combinations of capacities and speeds translate into power requirements that are typically about 5 to 10 percent lower than a tanker of the same dwt tonnage, less than 3 MW for ships smaller than 10,000 dwt, and a maximum of 15 to 25 MW for the largest vessels (fig. 5.4).



**Figure 5.4**

The propulsion-power demand of dry bulk carriers of different-size categories (based on MAN Diesel 2007a).

Container vessels have seen a tremendous rate of capacity increase in their short history (this is recounted in some detail in the next chapter), but even the largest ships operating today are not as large as the smallest



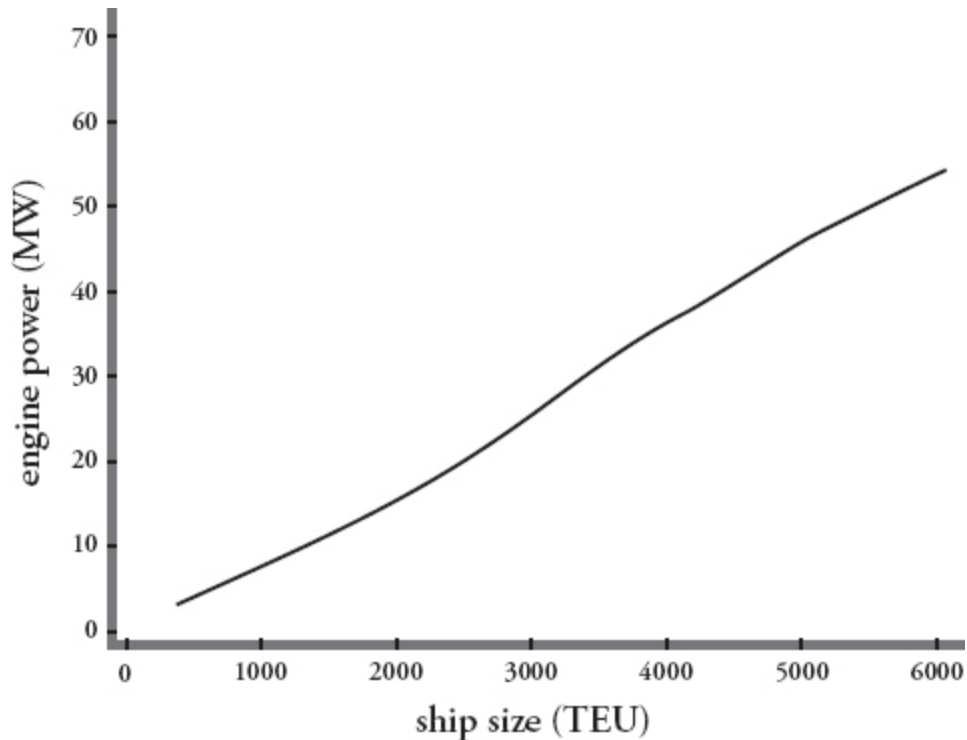
VLCCs. The capacity of these ships is not expressed in dwt as in the case of other cargo vessels but in terms of the maximum of standard-size containers—so-called twenty-foot equivalent units (TEUs). As both the height and width of a TEU is about 2.5 m, an additional row will increase the ship's breadth by nearly 3 m. Because an enormous variety of goods is now moved in containers (including every imaginable manufactured items, some bulk commodities, and even cars), their average loaded weight varies widely, but most are dimensioned to carry 12 to 14 dwt/TEU.

This means that small container ships (the so-called feeders that are used to bring containers to the large transoceanic vessels anchored in major container ports) with capacities of less than 1,000 TEUs are equivalent to bulk carriers of less than 14,000 dwt. The largest Panamax ships carry 3,000 TEUs (the equivalent of 37,000 dwt), while the largest post-Panamax vessels on order in 2008 were 10,000-TEU vessels equivalent to roughly 120,000 dwt. New classes have been already created for even larger ships: Suezmax for 10,000 to 12,000 TEUs and post-Suezmax for ships carrying more than 12,000 TEUs. Container ships have exceptionally high power requirements because they travel much faster than any other cargo vessels.

The most common speeds of container vessels are 15 to 19 knots (28 to 35 km/h) for small ships with up to 1,500 TEUs, 22 knots (nearly 41 km/h) for the Panamax class, and about 25 knots (just over 43 km/h) for the largest of today's post-Panamax vessels (MAN Diesel 2005b). The higher speeds are a direct consequence of larger ship sizes. Larger vessels take more time to load and unload, and higher speeds are designed to make up for this time loss to maintain established sailing schedules. That is why the coming class of ultra-large container ships should be expected to travel as fast as 26 knots (48.2 km/h), but higher speeds are unlikely because they would involve extraordinarily high fuel demand. It is these ships and not the much larger VLCCs that require the world's most powerful diesel engines to drive their huge propellers (fig. 5.5). Ships as large as 12,000 TEUs could still use a single propeller, but beyond that size they will have to have two main engines and twin screws.

Wärtsilä has been competing for the designation of the builder of the world's most powerful diesels with MAN, and MAN designed the first diesel rated at more than 100,000 bhp. This machine (model 12K98MC, rated at 101,640 bhp or 74.76 MW and 97 rpm) was built under license by Hyundai Heavy Industries, and it went into service in February 2006 (see

fig. 5.1). The twelve-cylinder engine is 16 m tall, 11 m wide, and 25 m long, and it weighs about 2,100 t. (MAN Diesel 2006b).



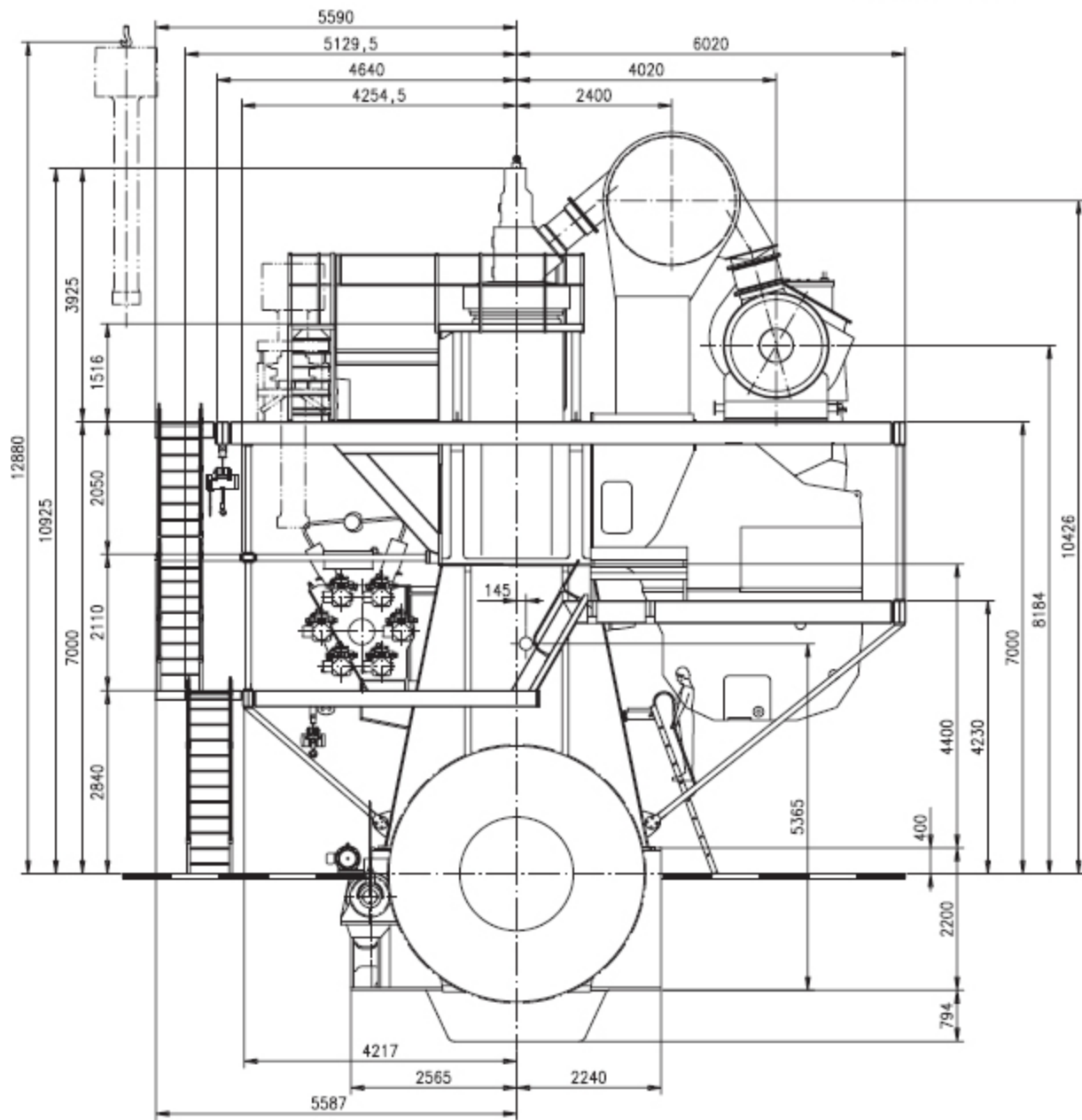
**Figure 5.5**

The propulsion-power demand of container ships of different-size categories (based on graphs in MAN Diesel 2005b).

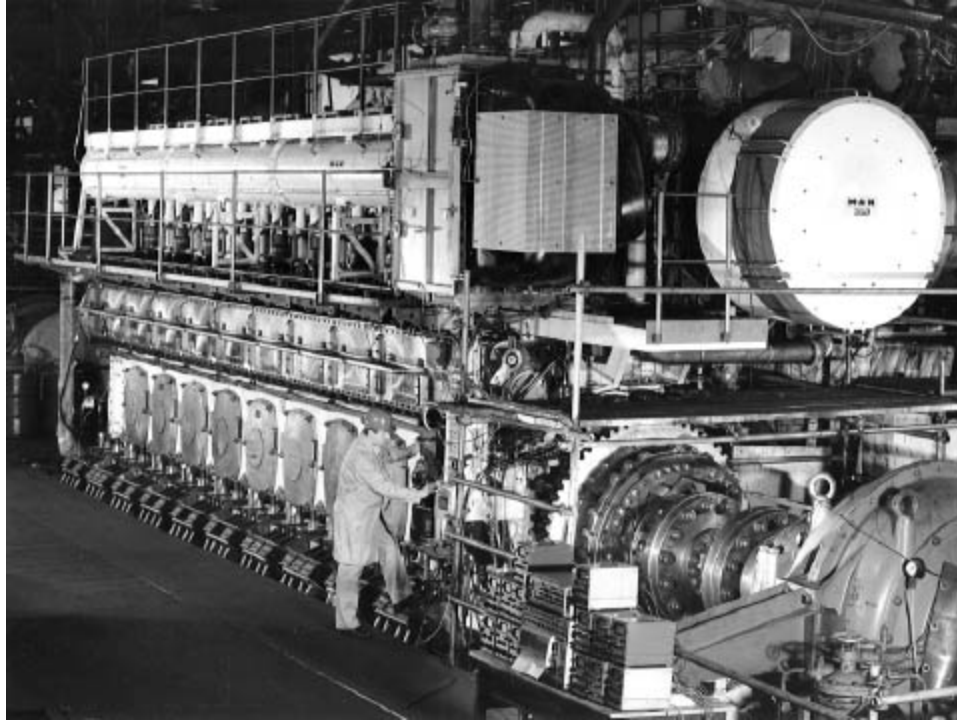
Its record rating lasted for only six months. In September 2006, the world's first fourteen-cylinder turbocharged diesel—Wärtsilä's RT-flex96C, built by the Aioi Works of Japan's Diesel United—began service on the *Emma Maersk* (Wärtsilä 2006). The new record-holder rated 80.1 MW (108,920 bhp) at 102 rpm. It is 27.3 m long and 13.5 m high, weighs 2,330 t and has a mass-to-power ratio of 28.72 g/W (Wärtsilä 2009b). Its cylinder bore is nearly 1 meter (960 mm), stroke length is 2.5 m, piston speed is 8.5 m/s, total displacement is 25,480 L (1,820 liters per cylinder), mean effective pressure is 1.86 MPa and its best performance is 163 g/kWh, corresponding to thermal efficiency of just over 50 percent (fig. 5.6). For comparison, the cylinder bore in my car, a Honda Civic, is 7.5 cm, piston stroke is 9.25 cm, displaced volume is about 0.4 liters per cylinder, and pressure is 950 kPa.

By 2008, modifications of the largest Wärtsilä engine raised the maximum rating to 84.42 MW—but the largest machine offered by MAN Diesel in its K98MC7 rose to 87.22 MW in fourteen cylinders at 97 rpm (MAN Diesel 2008c). And in 2005, MAN B&W Diesel had actually designed (in its K108ME-C engine series) a fourteen-cylinder 94-rpm machine rated at 97.3 MW that could be built if future large container ships require such power (MAN Diesel 2005a). This close contest for the world's most powerful diesel engine will almost certainly continue, but so will, at least for another decade or more, MAN's domination of the global market for large marine diesels. Company's notable post-World War II achievements range from the first two-stroke diesels with exhaust gas turbocharging in 1952 and nine four-stroke engines totaling 95.6 MW for a refurbished RMS *Queen Elizabeth 2*, in 1987 (fig. 5.7) to an electronically controlled series of engines with a common rail injection system first marketed in 2000, and dual-fuel combustion for four-stroke engines able to burn heavy oil, marine diesel, and even natural gas in 2006.

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DRIVING END



**Figure 5.6**  
A cross-section of Wärtsilä's fourteen-cylinder RT-flex96C marine engine. Detail of a drawing available at the Drawings section of the Wärtsilä Web site.



**Figure 5.7**

The diesel engine for the RMS *Queen Elizabeth 2*, built by MAN in 1987.

Photograph from MAN Bildarchiv.

Electronic controls have made it possible to eliminate quite a few mechanical parts—above all, chain drives, camshafts with cams, fuel-injection pumps, exhaust valve actuators, governors, and cylinder lubricators. These parts were replaced by hydraulic (power supply and cylinder units) and mechatronic (engine control system) components (MAN Diesel 2003). The result has been more precise timing, desirable injection pressure at any load, lower specific fuel consumption, and lowered emissions. For vessel operation, it has resulted in easier engine monitoring, the possibility of lower rpm for maneuvering, better acceleration, and better astern and crash stop performance. The common rail fuel-injection system is another important innovation introduced by Bosch and used for the first time by Alfa Romeo and Mercedes-Benz in 1997. Other carmakers followed (Renault in 2000, Volvo and BMW in 2001), and, as noted, MAN began to use this injection for its ME engines in 2000.

The key idea behind the technique is to separate the generation of the injection pressure from the injection itself. Fuel is pressurized by a pump independently of the engine speed and its fuel requirement and held in an

accumulator (common rail), from which it is led in rigid pipes to individual injectors and introduced as needed into the cylinders. Electronic controls maintain precise pressure and injection timing. The injection worked first in passenger cars at 135 MPa but by 2002, the third-generation version, relying on rapid piezoelectric switching (crystal oscillation) rather than on a solenoid, reached pressures of 180 MPa and by 2005 the maximum pressure was 200 MPa (compared to injection pressures of less than 35 MPa in traditional automotive diesels). Common rail systems have done away with the traditional camshaft, chain gear, fuel pumps, and hydraulic actuators. The result is better engine performance, lower fuel consumption, lower harmful emissions, and reduced engine noise.

MAN has maintained a high share of the global market for the two-stroke engines used in marine propulsion and electricity generation. In 2005, MAN (thanks largely to B&W designs) claimed about 75 percent of the market for these massive two-stroke diesels (although these largest engines are not made any more in Europe but under license in South Korea and Japan). This means that in 2005 about half of the world's total trade was moved from its places of origin to its markets by MAN's large two-stroke marine diesel engines.

Wärtsilä is now the world's second most important brand of large marine diesels, with about 20 percent of the global market (Wärtsilä 2009a). This Finnish-based company entered the diesel engine business more than a century after its establishment, and it acquired its current prominence thanks to its recent acquisition of Sulzer.

Sulzer Brothers of Winterthur was among the early (1898) licensees of Diesel's engine. The company made its first machine in 1903 and became an important licensee of new designs as early as 1909. By the 1920s, the company's innovative designs (the first two-stroke marine diesels, the first 1,000-millimeter bore engine for research, engines for electricity generation, railways, and submarines) made it a notable rival of MAN. The company's most notable post-World War II achievements include the first turbocharged two-stroke diesel engine (the Sulzer 6TAD48), installed in 1946 in the Winterthur factory; the extension of turbocharging to all marine low-speed two-stroke engines for ship propulsion during the 1950s; the development of electronically controlled fuel injection, first with four-cylinder engines beginning in the early 1980s; and the introduction of the world's first large, electronically controlled low-speed engine with

common-rail injection in 1998. By that time, diesel design and production were no longer a part of Sulzer. In 1989, Sulzer turned its diesel division into a separate company, and in November 1990 it sold it as New Sulzer Diesel Ltd (NSD) to German and Italian shipbuilding interests. As already noted, in 1997 NSD was acquired by Metra and turned into Wärtsilä NSD, which soon became simply Wärtsilä Corporation.

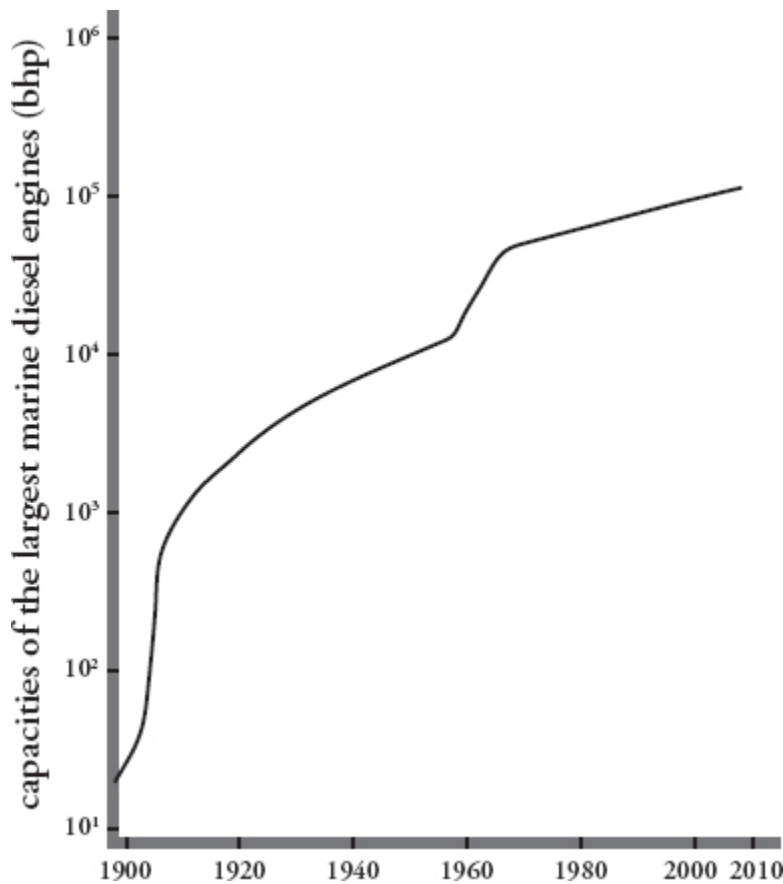
Because nearly all large diesels designed by the two leading European companies are now made in Asia, the breakdown of engine manufacturing by country looks completely unlike the breakdown by brand. In 2005, South Korea had about 38 percent of the total measured by aggregate engine power, and Japan claimed 26 percent (Akimoto 2006). China has risen to third place (nearly 15 percent of the total), with Germany (about 5 percent) and Taiwan (less than 3 percent) far behind. Asian engine makers thus have three-quarters of the global market for marine engines.

Japan—thanks largely to its global dominance of heavy shipbuilding in the late 1950s, 1960 and 1970s—was the first Asian country to become a leader in the manufacturing of large marine diesels. Mitsui Shipbuilding and Engineering launched its first vessel in 1917, and by 1926, it made a licensing agreement with Burmeister & Wain to produce marine diesels. Kawasaki and Mitsubishi became MAN licensees in 1929, and Yanmar, founded in 1912, produced its first diesel in 1933 (Mitsui 2009). Mitsui has been making electronically controlled engines since 2004. Compared to Mitsui, Daihatsu has been a latecomer. Its diesel division has been manufacturing engines of its own design only since 1966. Other Japanese makers of marine diesels not yet mentioned include Akasaka Diesels, Kawasaki Heavy Industries, Kobe Diesel, Niigata Power, Hanshin Diesel, and Makita.

South Korea has been the latest entrant into the manufacturing of large diesel engines and has very impressive achievements. Hyundai Heavy Industries (HHI), is now the world's leading shipbuilder as well as the world's top builder of massive two-stroke diesels for ship propulsion and electricity generation. In 1976, Hyundai began to manufacture marine engines under European license—and a quarter century later, in May 2001, the Hyundai-MAN Diesel partnership produced the world's largest engine rated at 93,360 bhp (HHI 2008). As already noted, in February 2006, HHI completed the 12K98MC, the first engine rated at more than 100,000 bhp (101,640 bhp or about 75 MW), and by 2005, the HHI's Engine &

Machinery Division (established in 1978) claimed about 35 percent of the global market share for large marine diesels.

A brief retrospective of marine diesel performance emphasizes the industry's remarkable record. The largest fourteen-cylinder machines now have capacities nearly six thousand times greater than Diesel's third prototype engine, which reached 19.8 bhp in 1897 (fig. 5.8). In 1903, three engines on the *Vandal*, the first diesel-powered vessel, had an aggregate capacity of 360 bhp, and in 1912, the *Selandia* had two eight-cylinder engines with a total of 2,100 bhp, two orders of magnitude above Diesel's prototype. In 1924, Sulzer introduced a 3,250-bhp engine for passenger ships followed by a 4,650-bhp design in 1929 (Brown 1998).



**Figure 5.8**

The capacities of the largest diesel engines, 1897 to 2008 (plotted from data in Diesel 1913; Brown 1998; MAN Diesel 2008a, 2008b; Wärtsilä 2009b).

In 1932 and 1933, Burmeister & Wain built an exceptionally large engine for the H. C. Ørsted power plant in Copenhagen, whose maximum capacity



of 22,500 hp (16.5 MW) remained unsurpassed for more than thirty years. The largest marine engines used by vessels during the 1930s were around 6,000 bhp, and by the late 1950s, they reached 15,000 bhp. In 1967, a new record was set at 48,000 hp in a twelve-cylinder engine. This power rating was nearly doubled by 2001 with MAN B&W-Hyundai's 93,360 bhp machine, and by 2008, the most powerful machines offered by the two leading producers were MAN's 115,000 bhp.

As for the engine performance, there was a slow but steady improvement from the net thermal efficiency of 26 percent achieved during the final 1897 test of Diesel's third prototype to 32 percent by 1910 (Clerk 1911). By 1950, MAN had a machine with 45 percent efficiency, leaving relatively little room for further gains. The first high-power two-stroke diesel with efficiency of just over 50 percent was introduced in 1982, and with that achievement large diesels have just about reached the practical peak of their performance. The latest models of the largest two-stroke machines have efficiencies of 52 percent, while the best four-stroke diesels now have efficiencies of around 48 percent. In a 50 percent efficient marine diesel engine, exhaust gas carries away most of the wasted energy (about 27 percent of the initial fuel content), air cooler removes about 14 percent, jacket water cooler and lubricating oil cooler disperse, respectively, about 5 and 3 percent, and the small remainder is lost by heat radiation.

## **Turbines in Flight**

The rapid post-1960 expansion of intercontinental jet travel required more powerful engines, and this demand was met by the first generation of large turbofan engines (whose genesis I review in the previous chapter). All of the three leading aeroengine makers introduced their distinctive designs. Pratt & Whitney had its JT9D (the first in a Boeing 747 in 1970), General Electric had its CF-6 (the first in a DC-10 in 1971), and (temporarily nationalized) Rolls-Royce put its RB211 for the first time on an L-1011 in 1972. As advanced, as revolutionary, and as large as they were, these engines were also relatively inefficient, quite noisy, and still not large enough for some new types of airplanes.

The need for higher efficiency became clear just a few years after these engines entered commercial service. OPEC's first round of oil-price increases more than quintupled the price of crude oil between 1972 and

1974, and the second round of rapid price rises (precipitated by the overthrow of the Iranian monarchy in 1979) brought them to nearly \$40/barrel by 1981. Higher engine efficiency and enhanced engine reliability also became necessary given the relentlessly growing volume of air traffic. The two key variables of civilian aviation—number of revenue passenger kilometers (pkm) and introduction of more routes (whether direct intercontinental flights or intranational connections)—as well as the total volume air cargo continued to increase annually on the global scale despite much more expensive kerosene and the higher cost of airplanes. At the same time, new plane designs required more powerful engines even as the increased volume of traffic led to the demand for less noisy airplanes.

All of these demands were addressed by the constant improvement of large turbofans, and new more efficient medium- and small-size engines were also introduced to cope with the growing volume of intracontinental traffic, particularly in Europe and Asia. Three interrelated general trends have been unmistakable: larger turbofans setting new thrust records have been introduced even as the overall quality (efficiency, reliability, ease of maintenance) of commercial aviation engines has been steadily improving and as their noise generation has been declining. Much like the case of diesel engines, where MAN Diesel, the direct descendant of the machine's developer and original maker remains the dominant producer more than a century later, the companies that commercialized gas turbines for flight during the 1940s—Rolls-Royce in the United Kingdom and General Electric in the United States—are still the two leading forces of the market.

Soon after World War II, this enduring duo was joined by a smaller American company with a long tradition of manufacturing aeroengines. The Pratt & Whitney Aviation Company was set up in 1925, but during World War II, it was too busy to produce piston aircraft for the country's war effort. It entered the jet age only in 1948 with an engine for a U.S. Navy plane, and in 1952, it introduced its model J57, the precursor of its first commercially successful J57 engine used on the Boeing 707 and DC-8. This small oligopoly has worked remarkably well. The three companies (joined by other companies to share risk and revenues on some new designs and recently also cooperating directly on some projects) compete to design and build engines for the same types of aircraft, and the aircraft makers prefer not to rely on a single make for a particular plane to provide flexibility and to lower prices.

General Electric's aeroengines division has the largest share of the global jet-engine market, and it supplies a complete range of military and civilian turbojets and turbofans (General Electric Aircraft Engines 2009a). Its commercial aviation offering ranges from low-thrust machines for executive jets (such as the CF34 for the Bombardier Challenger or the CFE738 for the Falcon) to large turbofans that include another enduring series (the CF6 with ratings up to 320 kN) and the GE90 family. And CFM International, GE's joint venture with French Snecma, dominates the market for medium-thrust designs for short- to long-range aircraft as its engines (above all, the enduring CFM56-3 found in some two thousand different versions of the Boeing 737) power about 70 percent of all single-aisle aircraft with more than a hundred seats. CFM International also makes the CFM56-5C (151 kN), the exclusive power plant for the long-range, four-engine Airbus A340. GE's latest new designs are GENx for the new Boeing 787 and the GP7000 produced by Engine Alliance, a joint company of GE and Pratt & Whitney, for the superjumbo Airbus A380 (Engine Alliance 2009).

Since the mid-1990s, intercontinental aviation, that essential ingredient of economic and social globalization, has been relying heavily on the GE90 family of engines that had its origins in the early 1990s. The first version was designed for the Boeing 777 and commissioned by British Airways for the company's new fleet of this long-range wide-body aircraft. The engine's initial variant, GE90-90B, was originally certified in 1995 at 376 kN, but soon its rating was raised to 404.4 kN (90,000 pounds), and it was put into service in early 1996. A larger (94B, 425 kN) and a smaller (77B, 332 kN) variant followed, and in July 1999 Boeing chose General Electric to develop a more powerful version of the GE90 engine to power all long-range twin-engine Boeing 777-200LR (301 passengers in three classes, in service since 2006) and 777-300ER aircraft (359 passengers, in service since 2004).

The ER has nearly the same passenger capacity as the Boeing 747-400 (365 versus 316 people), but it can fly about 9 percent farther on just two engines, while the LR, with 301 passengers in a three-class configuration, has the greatest maximum range of any jetliner (17,370 km compared to 13,450 for the 747-400), making it possible to travel directly from the eastern coast of the United States to Southeast Asia or from Europe to Australia. GE90-115B (its specification called for 115,300 pounds or 512

kN of thrust) is a derivative of the original GE90. As was its predecessor, it was developed with the participation of Snecma Moteurs of France, Avio of Italy, and IHI of Japan to provide an unmatched combination of reliability, fuel efficiency, and noise reduction. Moreover, the two engines are also 10 to 15 percent cheaper to maintain those of a three- or four-engine aircraft (Horibe et al. 2004).

After twenty months of trials, the engine was certified in July 2003 at 512 kN, which made it officially the world's most powerful aeroengine, and even that unprecedented level was surpassed during initial ground testing (conducted at General Electric's outdoor test site near Peebles, Ohio), when the thrust reached 568 kN (that is, nearly 2.5 times that of the JT9D that powered the first Boeing 747s and the DC-10). As for its main features, the engine has a single-fan, four low-pressure compressors and nine high-pressure compressors, an overall pressure ratio of 42 to 1, a bypass ratio of 9 to 1, a two-stage high-pressure turbine and a six-stage low-pressure turbine, a fan diameter of 3.25 m, a length of 5.1 m and a dry weight of 8.28 t (General Electric Aircraft Engines 2009a; [fig. 5.9](#)). The engine's test flights began in 2002, and Air France was the first airline to use it on its Boeing 777 planes in April 2004.

The improved performance of GENx engine, designed to power Boeing's innovative twin-engine 787, is due to a cleaner-burning combustor and a counterrotating low-pressure turbine. Its specific fuel consumption is 15 percent lower than that of the engines it will replace. It can stay on wing 30 percent longer than previous designs and use 30 percent fewer parts for maintenance. Its emissions are only a small fraction (as much as 95 percent below current regulatory limits) of previous designs, while its noise is reduced by as much as 30 percent. The GENx engine series will eventually replace the company's best-selling CF6 engine family.



**Figure 5.9**

The GE90-115B is the world's most powerful turbofan aeroengine. Photograph courtesy of GE Aeroengines.

The second American gas turbine maker, Pratt & Whitney, is the smallest of the trio of aeroengine manufacturers, and its family of high-thrust PW4000 engines was launched with a 235-cm-diameter turbofan (94 inches, hence the name PW400-94) that was certified at 231 to 276 kN (Pratt & Whitney 2009b). These engines have been powering large jetliners since 1987. The first derivative, designed to power the Airbus A330 twinjet, was PW4000-100, a 250-cm-diameter turbofan rated at 287 to 311 kN introduced in 1994 as the industry's lightest engine with the most advanced nacelle (fig. 5.10). The second derivative—the PW4000-112, a 280-centimeter-diameter turbofan rated at 386 kN—was introduced to in 1995 (first with United Airlines) to power the Boeing 777 twinjet.

The third variant, the W4090, is certified at 408 kN and began its service on the Boeing 777-200ER in 1997. A decade elapsed before Pratt & Whitney introduced a new engine. The PW6000 is a small turbofan (rated at 80 to 107 kN) designed to power an increasingly popular type of small (fewer than a hundred passengers) jetliners, such as the Canadair CRJ and Embraer. The company's forthcoming innovation is the PurePower PW1000G engine, which has been selected for the next generation of MRJ

(Mitsubishi's Regional Jet) as well as for the Bombardier's CS series of aircraft (Pratt & Whitney 2009c).



**Figure 5.10**

The P&W 4000-100 turbofan.

Photograph available at the Pratt & Whitney Web site.

The engine's gear system will make it possible to operate the fan at optimum (that is, slower) speed while the low-pressure compressor and turbine rotate at a higher speed. This arrangement will lower engine weight, fuel consumption, emissions, and maintenance costs. In August 1996, Pratt & Whitney formed Engine Alliance with General Electric, and the new company's GP7200 engine draws on the two design traditions that have made affordable intercontinental flight—the GE90 and PW4000 families of turbofans (Engine Alliance 2009). The new engine is built around the GE90 core and the PW4000 low-pressure compressor and turbine, and its versions (initially 340 kN and later 363 kN) are offered for different configurations of the Airbus A380, competing with Rolls-Royce's Trent 900.

After Rolls-Royce was returned to private ownership in 1987, the decision was made to develop an entire new family of engines based on the

(eventually) successful triple-spool RB211 design. With this more complicated arrangement, the fan has its own shaft, and the low- and high-pressure turbines can be run close to their optimum speeds (Rolls-Royce 2009). This decision has made it possible for the world's second-largest aeroengine maker to offer more than a dozen models covering the entire spectrum of thrust demands. Returning to the tradition of naming its engines after rivers, the first member of the Trent family, the Trent 700 (designed for the Airbus 330), was certified in 1994 in two versions of 300 and 316 kN with a 5 to 1 bypass ratio. A year later came the certification of the Trent 800 developed for the Boeing 777, with up to 423 kN of thrust and a maximum bypass ratio of 6.2 to 1. The third entry came in 2000 with the Trent 500, a smaller turbofan (236 to 287 kN) to be used by the four-engine long-range Airbus A340.

The development of the Trent 900, the fourth addition to the Trent family, was shared with seven foreign partners in Europe and Asia. The engine entered regular service (with Singapore Airlines superjumbo on the Singapore-Sydney route) in October 2007. Its basic specifications are a thrust of up to 355 kN, air-mass flow 1,245 kg/s, a fan diameter of 290 cm, fourteen compressor stages (eight intermediate and six high-pressure), seven turbine stages (five low-pressure, one high-pressure, and one intermediate-pressure), and a bypass ratio 8.5 to 8.7 (Rolls-Royce 2009).

Much like the designs of its two competitors, the Trent 900 is considerably less noisy (making it possible for the giant Airbus A380 to generate only about a third of the noise level produced by a 150-seat aircraft of an older design) and less polluting. Its other notable features are a smaller and lighter fan containment (because it is made from titanium, it can do without Kevlar wrap) and a counterrotating high-pressure shaft. The latest addition to the series, announced in 2004, is the Trent 1000, which is designed to power the Boeing 787 in competition with General Electric's GENx and developed with six risk- and revenue-sharing partners in Japan, Europe, and the United States who have a 35 percent stake in the venture. The engine (rated at 284 kN) was certified in August 2007, but its deployment has been repeatedly postponed due to the Boeing's problems with completion of the new aircraft.

A detailed study of learning, technical competition, and network structure in the aeroengine industry based on relevant performance characteristics for all designs introduced between 1958 and 1997 indicated an extremely close

contest among the three turbine makers and their alliances (Bonaccorsi and Giuri 2001). Comparisons of the highest bypass ratios show the frontier designs moving from Pratt & Whitney to General Electric and CFM, then to CFM alone, and finally back to General Electric. Overall pressure ratio has seen an even keener contest, with the frontier designs moving from Pratt & Whitney to Rolls-Royce, then to General Electric, back to Pratt & Whitney, again to Rolls-Royce, and finally to GE. In terms of specific fuel consumption, the post-1972 achievements have been virtually identical for all the makers.

Inevitably, all of the large state-of-the-art turbofans share a number of basic attributes besides better fuel economy and reduced noise. Their high-flow swept fan blades—certainly the most elegant feature seen by air travelers (fig. 5.11)—are made from composite materials, carbon fibers, and resins (not of titanium, as were fans in the 1960s). As already noted, early problems with these composites contributed to the bankruptcy of Rolls-Royce in 1971, but the latest carbon-reinforced epoxy blades are now 100 percent defect-free—that is, there are no wrinkles or voids in their fibers. All of the latest turbofan models are also equipped with advanced monitoring systems that make it much easier to prevent serious problems and to perform necessary maintenance. Moreover, all of them are designed so that a new engine can be transported in a Boeing 747 freighter to replace rapidly an engine that has suffered a serious malfunction.

The continuous reliable operation of these largest turbofans is a marvel of material endurance and precision engineering. During takeoff, turbine rotor blades may reach more than 1,500°C, a temperature that is higher than the melting point of the rotating metal. As a result, they must have elaborate internal air cooling, and every blade (made of nickel-based monocrystalline superalloys) now acts as a multipass heat exchanger. The shared requirements of a high thrust and a high bypass ratio make them the largest and the heaviest aeroengines ever built. Their fan diameters are in excess of 2.5 m and the largest fans, at just over 3 m, are equal to the diameter of the fuselage of the Boeing 727.

The dry weight of the heaviest engine (the GE90-115B at 8.28 t) is almost identical to the weight of the entire DC-3, the most popular piston-driven passenger airplane. Unlike relatively long turbojets, all high-bypass high-thrust engines appear more chunky (their length-to-fan diameter ratio is less than 1.6), but their specific thrust-to-weight ratios are in excess of 6



to 1 or even 7 to 1. This enormous specific power means that modern turbofans can serve any practical aircraft design—from small regional jets carrying only around fifty people to superjumbo designs capable to fly up to a thousand passengers in an economy configuration.

They also share unprecedented reliability, which has translated into the extraordinary safety of modern commercial aviation. As a part of certification testing, all turbofans have to undergo many prescribed hours of running at high levels of thrust and must also pass bird-ingestion tests during which 1.13- and 3.63-kg birds must pass through the engine without any thrust loss and with continuing response to all throttle commands for the subsequent twenty minutes. All new turbofan designs also have to demonstrate blade containment and acceptable trailing blade damage in the case of sudden blade loss (blade out) and pass demanding water- and hail-stone-ingestion tests (fans must cope with ingesting 53,000 liters of water per hour and 300,000 1.25-cm hailstones fired at the fan at about 320 km/h in half a minute. This extraordinary reliability has made it possible to deploy twin-engine aircraft on transoceanic routes where they are more than one hour of flying time away from the nearest airport.





**Figure 5.11**

The massive fiber-and-resin blades of three large turbofan engines. General Electric's GE90-115B; facing page: Rolls-Royce's Trent 1000 and Pratt & Whitney's GP7000.

Photographs available at the Web sites of GE Aircraft Engines, Roll-Royce, and Pratt & Whitney.

This old sixty-minute restriction, reflecting a much less reliable performance of piston engines, was enacted by the U.S. Federal Aviation Administration (FAA) in 1953, and it put most of the world's oceans out of

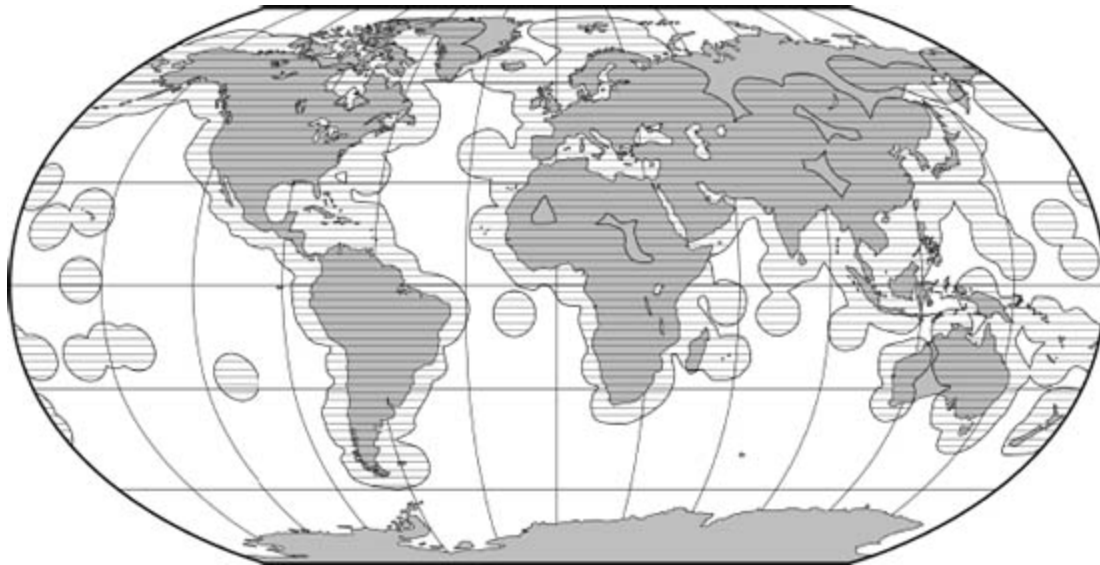
the reach of twin-engine jetliners (fig. 5.12). Most notably, it made it impossible for them to fly the shortest (great-circle) routes to serve the world's busiest and most lucrative markets connecting North America and Europe. This rule was removed only when the indisputably proven reliability of modern turbfans made it possible to approve Extended-range Twin-engine Operational Performance Standards (ETOPS) that allowed flights that were longer than sixty minutes from diversionary airports, beginning with a Boston to Paris flight on February 1, 1985 (Bachtel 2003). The two-hour ETOPS greatly expanded the best connection opportunities by opening up virtually the entire North Atlantic for great-circle crossings and by rapidly making the twin-engine Boeing 767 the dominant trans-Atlantic airplane. Its use on these routes surpassed that of the four-engine Boeing 747 by 1993, and its weekly crossings now total over two thousand flights (Boeing 2006, 2009d).

Great-circle crossings of the North Pacific were next and in 1988 the ETOPS maximum was raised to three hours. This change was useful even in the North Atlantic, when one of the northern diversionary airports in Greenland or Iceland was unavailable due to bad weather. The PW 4000 was the first engine to qualify for the two-hour ETOPS even before entering the service, and the PW 4000-112 was the first engine approved for 207 minutes of ETOPS. In March 2000, it became possible to use twin-engine aircraft on routes where they would have to fly up to 207 minutes on a single engine to reach the nearest airport (Reich 2003).

Finally, I present a brief retrospective of the remarkable record of jet engines from their first working prototypes in the late 1930s and the early 1940s to their mature designs of the first decade of the twenty-first century. As with diesels, a lead indicator is a relentless rise in unit capacities—in this instance, measured in terms of maximum (takeoff) thrust (fig. 5.13). The extreme difference between von Ohain's 1939 He S3B (rated at 4.4 kN) and the world's most powerful aeroengine, General Electric's GE90-115B (certified in 2003 at 512 kN and tested at as much as 568 kN) is two orders of magnitude (116-fold).

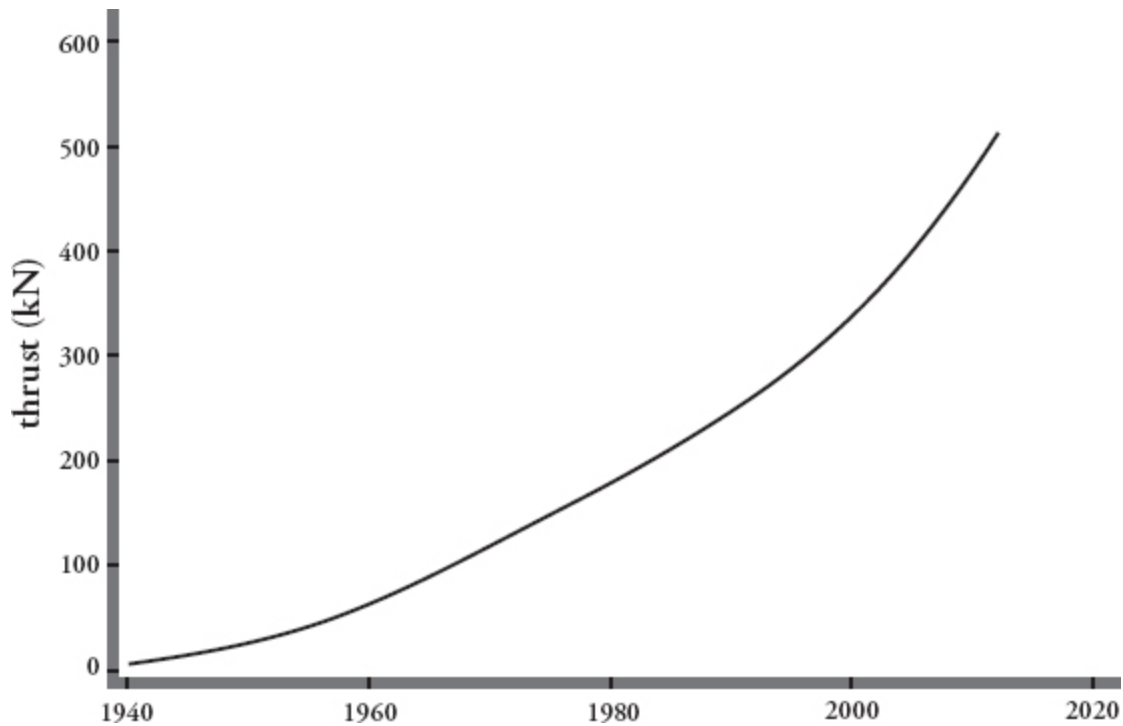
Other engine specifications follow with corresponding increases. The He S3B and Whittle's W.2 had overall pressure ratios of, respectively, 2.8 and 4.4. By 1950, the Avon reached about 7.5; by 1970, the JT9D surpassed 20; by the mid-1980s, the ratios were over 30; and in 2003, the GE90-115B reached 42 (fig. 5.14). The air-mass flow of both Whittle's and von Ohain's

design was about 12 kg/s while the GE90-115B handles about 1,360 kg/s. The dry mass of jet engines rose from 360 kg for the Hs S3B and 385 kg for the W.2B to 1,310 kg for the Avon, just over 4,000 kg for the JT9D, and nearly 8.3 t for the world's largest engines today. But because thrust has increased faster, an all-important thrust-to-weight ratio of commercial aeroengines rose from just 1.38 for von Ohain's and 1.6 for Whittle's pioneering designs to nearly 4.0 by the late 1950s and then to mostly around 5.5 during the late 1980s and the 1990s, with the GE90-11B reaching 6.3 in 2003 (fig. 5.14).



**Figure 5.12**

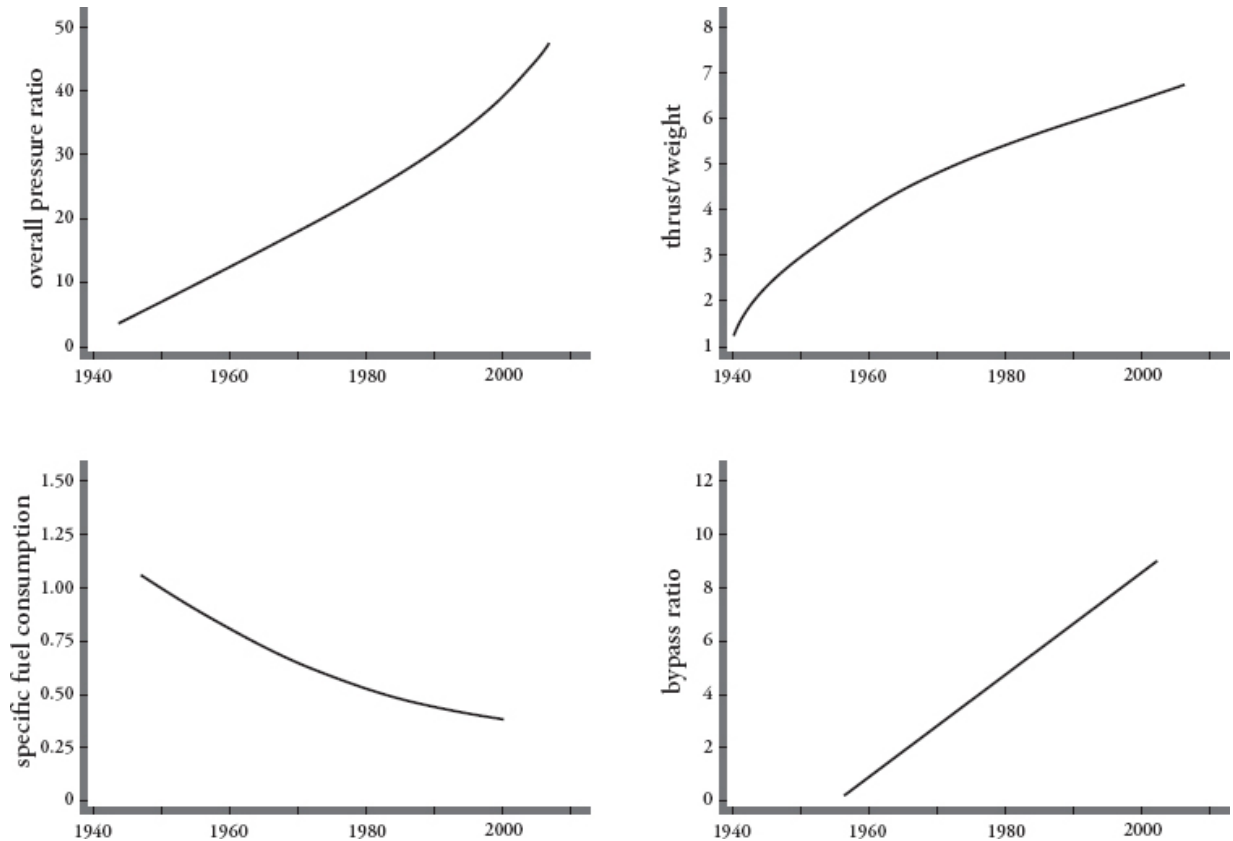
Restricting commercial aircraft to sixty minutes of flight with a single engine put most of the world's ocean beyond the reach of twin-engine jetliners (based on a map in Bachtel 2003).



**Figure 5.13**

The increasing maximum thrust of aviation gas turbines, 1940 to 2010 (based on Ballal and Zelina 2004).

A long-term trend toward larger, slower-rotating, more efficient, and more reliable two-stroke marine diesels has its counterpart in the trend from turbojets to high-bypass ratios. The turbojets of the 1940s and 1950s had no bypass air flow, the low-bypass turbofans of the late 1950s included Rolls-Royce's Conway (with a bypass ratio 0.3 to 1) and those of the early 1960s included Pratt & Whitney's JT3D (at 1.4 to 1), the first high-bypass designs of the late 1960s included Pratt & Whitney's JT9D (at 4.8 to 1), and the engines with rising bypass ratios culminated in 2003 with the GE90-115B (at 9 to 1) and the Trent 1000 (at 11 to 1) (fig. 5.14). Naturally, higher bypass ratios have required larger fans: their diameters increased from 125 cm for Conway and 135 cm for the JT3D to 235 cm for the JT9D, 250 cm for the P&W 4000, and 325 cm for the GE90-115B. As for the specific fuel consumption, the early turbofans needed 20 to 25 percent less fuel than the turbojets, the high-bypass turbofans of the 1970s and 1980s consumed up to 35 percent less fuel, and today's best designs need only about half as much fuel per unit of thrust as the engines of the 1950s (fig. 5.14).



**Figure 5.14**

The improving performance of aviation gas turbines. From top left, clockwise: increasing overall pressure ratio; increasing thrust-to-weight ratio; increasing bypass ratio; decreasing specific fuel consumption, 1945 to 2005 (based on Ballal and Zelina 2004).

## Other Mobile and Stationary Uses

Ocean shipping is not the only transportation niche that is indispensable for the global economy and whose smooth functioning depends on diesels. Those powerful, reliable, and durable machines also make enormous contributions when used in the stationary mode. Similarly, jet engines are not the only gas turbines that are critically important for wider economic integration and for improved productivity. The other two transport market niches where diesel engines either are dominant or claim large shares of installed power are freight shipments by railroads and trucks, and their main stationary role is as electricity generators. Stationary gas turbines have recently become one of the most common choices for highly efficient electricity generation, and the machines also serve important niches as the

prime movers of compressors, particularly those moving natural gas in pipelines.

In all major economies (and particularly in large territories with unevenly distributed populations, such as in the United States and Canada), railroads provide an indispensable link in the chain of global container shipments as they move the boxes unloaded in large ports many hundreds and thousands of kilometers away to principal urban distribution centers from which they are then delivered by trucks to their final destinations. Diesel locomotives also pull modern passenger trains traveling at speeds in excess 100 km/h but the fastest passenger rail service—pioneered during the 1960s by Japan’s *shinkansen* and later by the French *train à grande vitesse*, whose speeds are in excess of 300 km/h—relies on electric traction.

Public perception of railroads in the era of microchips is one of an old, mature, and increasingly marginal industry where little innovation has taken place. This perception is completely wrong: freight railroads remain essential for the operation of all large modern economies and have met new challenges by constant innovation. No less important, the specific energy intensity—energy per mass and distance, usually expressed in joules per ton per kilometer (J/tkm)—of rail transport and its emissions of air pollutants and greenhouse gases are much lower than the comparable rates for trucking (Assn. of American Railroads 2009a). And because a standard freight train carries a load that is equivalent to that of several hundred large trucks, highway congestion—a problem that is estimated to cost the United States close to \$80 billion annually (Texas Transportation Inst. 2007)—would become much worse if a substantial share of freight were not moved by railroads. Finally, infrastructural cost of new railways (typically \$1 million to \$2 million/km) is much lower than for highways (commonly \$9 million to \$10 million/km).

Although American passenger rail transport remains inferior to EU or Japanese achievements (both in terms of overall capacity and technical performance), American freight railroads have the longest active track, operate the largest number of locomotives, carry by far the largest amount of cargo, and provide the world’s most cost-effective transportation service on land. In 2005, America’s class I railroads had just over 150,000 km of track (compared to less than 150,000 km in the European Union’s fifteen countries and less than 65,000 km in China), and in 2006, those railroads

operated nearly 24,000 locomotives (compared to about 18,000 in the European Union, 17,000 in China, and 8,000 in India (World Bank 2008).

In 2006, U.S. railroads carried nearly 1.8 Gt (or roughly twice the aggregate EU15 load) for the total of about 2.5 trillion tkm. They moved more than 40 percent of the country's freight, a share much higher than in all other major Western economies with the exception of Canada. Canada's share is about 50 percent, French and German shares are about 20 percent, Italian and British shares are less than 10 percent (reflecting short distances from the seacoast), and Japan (where sea transport dominates) moves only about 5 percent of its freight by rail. America's railroads carry nearly a third of all traded grain, two-thirds of all coal, and some 70 percent of all cars, and they have done so with an unmatched productivity and with admirable energy savings. Between the passage of the Staggers Rail Act in 1980 (it allowed for a substantial deregulation of the industry) and 2007, employee productivity was up by about 430 percent, locomotive productivity by 124 percent, and fuel efficiency by 85 percent, while the inflation-adjusted rates were 54 percent lower (Assn. of American Railroads 2009b). This would have been impossible without more reliable, more durable, and more efficient diesel locomotives that move virtually all of America's freight, while in Europe they account for about half of the locomotive stock, in China for nearly 70 percent, and in India for about 60 percent. Modern diesel locomotives are actually hybrid vehicles. Diesel engines (typically two-stroke, twelve-cylinder machines with the largest units rated above 30 MW) are their prime movers, but their reciprocating motion is not transmitted to wheels. Instead, it is used to generate electricity, and electric motors drive the train (Lamb 2007). The correct term is thus *diesel-electric locomotive*. Diesel-electrics are directly powered in the same way as other electric locomotives, but unlike the machines that tap electricity from overhead wires, they carry their own onboard source of power. In addition, the trains have also a separate diesel engine and a generator that is used to supply electricity for other needs than propulsion (lighting, heating, and cooking).

Besides their much higher fuel efficiency, diesel engines could also operate with less maintenance and fewer overhauls, required less frequent refueling, and hence could spend more time earning their keep. America's first diesel-powered 225-kW (300-hp) engine, produced by the American Locomotive Company in cooperation with General Electric and Ingersoll-



Rand, was completed in 1924. In 1930, the Electro-Motive Corporation (EMC) was bought by General Motors, and it was known as GM's Electro-Motive Division (EMD) until 2005, when it became an independent company called Electro-Motive Diesel. EMD provided the industry standard during the 1930s (Schafer 1998). Its E engine series (the EA model was introduced in 1937 with two 900-hp twelve-cylinder diesels) was developed initially for passenger service—above all for the Burlington Zephyrs, the most famous streamlined trainsets (their engines were permanently attached to several coaches).

The first engine of its FT (freight train) series (introduced in 1939) rated 2 MW (2,700 hp) from a combination of equally sized main cab and a booster unit, and it was welcome because of its reliability and easy maintenance. World War II restrictions postponed a rapid diffusion of freight diesels until the late 1940s, but a decade later hardly any class I railroads relied on steam power. The company lost its primacy to General Electric locomotives during the 1980s, but its latest model, the 3.2-MW (4,300-hp) SD70Ace (launched in 2005), is one of the most efficient and the least polluting designs on the market. General Electric began its conquest of the American freight diesel market with its Universal series. The first model (the 2,500-hp U25B) was introduced in 1956, and more powerful models followed during the 1960s and 1970s.

GE's latest Evolution Series has engines as powerful as their immediate predecessors (the AC 440 with 3.28 MW at full throttle), but they operate with higher efficiency and lower emissions (fig. 5.15). About half of all U.S. diesel locomotives in operation today are General Electric designs that have been introduced since the 1960s. During that time, the rated power of the largest machines has gone up nearly 80 percent, but the continuous tractive effort rose from about 27 to 75 tons, nearly a 2.8-fold increase. China's rapidly expanding freight traffic also relies primarily on diesel locomotives, and these machines are used for shunting, feeder traffic, and less frequented lines—even in those European countries (including Germany and Switzerland) where all main trunk lines are electrified (Kollamthodi 2006).

Railroads transport all kinds of raw materials (including stone, grain, wood, and coal) within countries or to and from major trading ports, but their impact on economic globalization has been most obvious thanks to their massive container shipments. Containerization on the seas was

preceded by containerization on railways, although the earliest form of these freight shipments came with wheels attached. In 1952, the Canadian Pacific Railways was the first company to use flat cars for the intermodal transport of truck trailers—the rectangular boxes with permanently attached wheels. This piggybacking is known in the industry by its acronym TOFC (trailer on flat car), and before the end of the 1960s, it became common as increasingly longer flatcars (up to 25 m) were used to carry larger trailers.



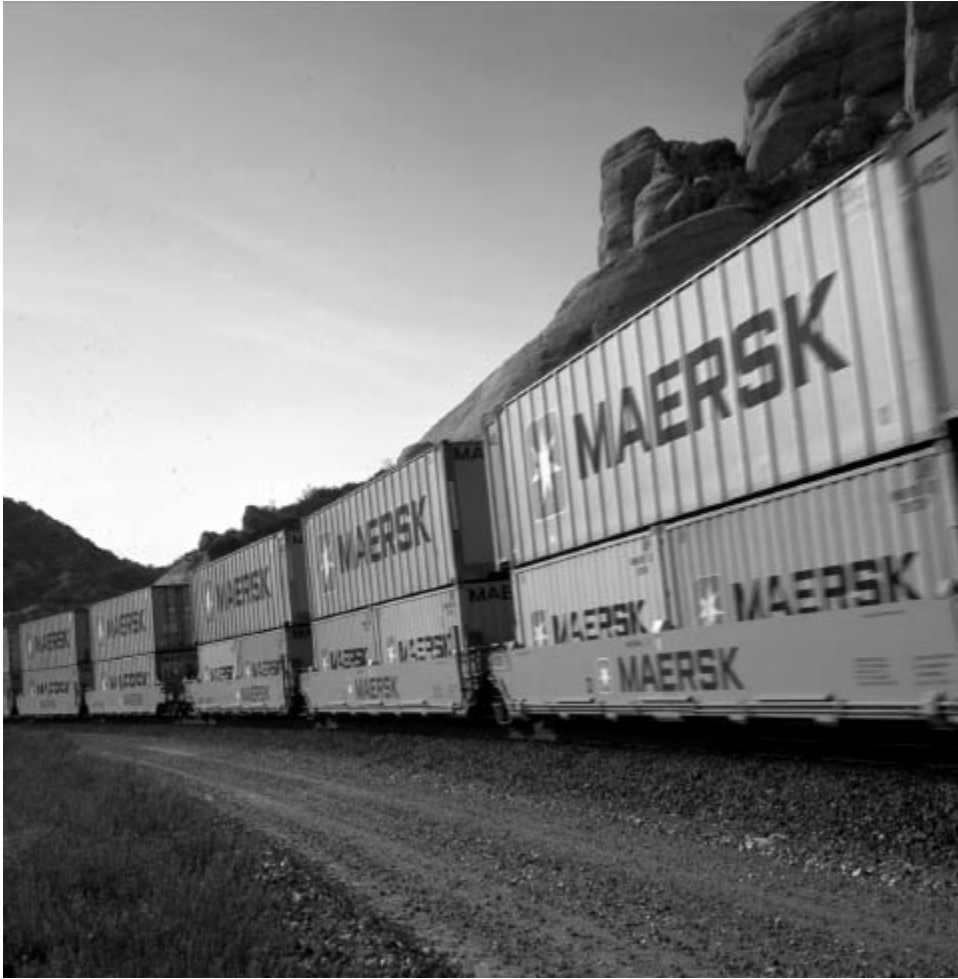
**Figure 5.15**

The GE Evolution diesel locomotive.

Photograph available at the GE Transportation Web site.

In the 1970s, even as the shipments in box containers became the norm in maritime freight transport, TOFC continued to dominate the North American railroad shipments of nonbulk commodities, but as the U.S. data indicate, the subsequent switch to the COFC (container on flat car) mode was quite rapid. In 1985, nearly 80 percent of all intermodal moves on U.S. railways involved trailers, but by the year 2000, 75 percent of all carried units were containers (Intermodal Assn. of North America 2009). The switch was helped by the general adoption of double-stacking. Southern Pacific used the first double-stack car in 1977, and APL introduced Stacktrain (since 1999 owned by Pacer Stacktrain) and began to double-stack large 48-foot containers in the mid-1980s. COFC trains now routinely carry more than 100 containers ([fig. 5.16](#)).

Over the past three decades, intermodal transport has been the fastest-growing segment of the U.S. freight railroad industry, with aggregate shipments rising from less than 3 million units (trailers and containers) in the late 1970s to more than 12 million units by 2006. As a result, it has also become (at about 22 percent in 2007) the industry’s single largest source of revenue. This expansion has required considerable investments in new locomotives, new freight cars, new and enlarged loading and distribution terminals, and the raised clearances on bridges that are needed to allow the doublestacking of containers.



**Figure 5.16**  
Doublestacked containers on Maersk’s delivery train.  
Photograph available at the Maersk Web site.

Trucks are commonly the first and almost always the last transportation link in the global production, transportation, and distribution system. As for

the prime movers of road trucks, the share of diesel engines depends heavily on the truck size, intensity of operation, and length of typical trips (Charles River Associates 2000). In the United States, most light-duty trucks (classes 1 and 2, pickups, and cargo vans) have gasoline engines, 40 percent of medium-duty trucks (classes 3 to 5, gross weight of 6.4 to 8.8 t, including cab-forward trucks with van body and walk-in vans) are powered by diesels, the share rises to 50 percent for light-heavy duty vehicles (class 6, gross weight of 8.8 to 11.8 t, including stake and beverage trucks), 91 percent for all heavy trucks (classes 7 and 8 in excess of 11.8 t, including dump and cement trucks and all conventional heavy tandem machines), 98 percent for truck tractors with a single trailer, and 99 percent for those with double trailers.

About 85 percent of trucks driven more than 120,000 km a year have diesel engines, and although only about 6 percent of all trucks used for local transport are diesel-powered, that share rises to 30 percent for those making typical trips up to about 300 km and to two-thirds for trucks whose trips average more than 800 km. Because of traditionally higher fuel costs in the oil-importing countries of the European Union and Asia, similar relationships between the share of diesel engines and truck size, operation intensity, and average trip length are even more pronounced in other major Western economies, with European and Japanese makers offering diesel-powered trucks all the way down to class 3 (the smallest medium-duty vehicles).

The overwhelming dominance of diesels in the heavy-truck category is not only a matter of superior engine efficiency and hence of lower operating costs. The largest road trucks require engines in excess of 370 kW, or 500 hp (Mack's Titan series has a 451 kW or 605-hp model), and such machines are not available in gasoline-fueled versions. All U.S. or foreign manufacturers build class 8 trucks only with diesel engines. Given the wide range of truck sizes and a correspondingly large range of diesel engines, it is not surprising that their production is not as heavily concentrated as that of large marine diesels, where there is now essentially a global duopoly of designs. Smaller trucks are produced by most major auto makers. In the United States, the Detroit Diesel Corporation, the successor of General Motor's Diesel Division, has a high share of the country's heavy-duty truck-engine market (Detroit Diesel 2009).

And only diesel engines can be found in the large off-road trucks that are a common sight at coal and ore mines around the world. Currently, the world's most powerful wheeled vehicles are the mining trucks made by Liebherr (the T 282 B) in Germany and by Caterpillar (the 797B) in the United States (Liebherr 2009a; Caterpillar 2009). The former trucks have a 3,650-hp (2.7 MW) engine that drives two electric motors (hence it works much like a diesel-electric locomotive) and load capacity of 360 t. The latter vehicles are powered by a 2.5-MW (3,370-hp) engine, have a nominal load of 380 t (and carry up to 400 t), and are used to haul tar sands from the mine face to the upgrading facilities in northern Alberta ([fig. 5.17](#)).



**Figure 5.17**  
Caterpillar's largest off-road truck, the 797B.  
Photograph available at the Caterpillar Web site.

An important innovation that will help to maintain the dominance of diesels in heavy trucking is the introduction of selective catalytic reduction by injecting urea mist into truck exhaust. By the end of 2008 more than half a million European diesel trucks used the method to lower the emissions of nitrogen oxides from the diesel exhaust by as much as 90 percent and to near zero when used in conjunction with particulate filters. Since January 2010 urea tanks are mandatory not only on new U.S. diesel trucks but also on buses, cars and SUVs manufactured in the country, and the rule will be extended to off-road vehicles by 2015. These measures will help to reduce the incidence and severity of photochemical smog but they will have impact on the price of urea, now the world's most important nitrogen fertilizer (IFDC 2008).

A globalized economy could not function at its current intensity without the ubiquitous presence of heavy-construction and earth-moving machinery and without a high level of agricultural mechanization. Nearly all of the heavy machinery that is used to build roads, bridges, tunnels, houses, commercial, and industrial enterprises is powered by diesel engines. The two globally most prominent makers of these machines are the United States' Caterpillar and Japan's Komatsu. About two-thirds of America's farm machinery—including all large tractors and self-propelled harvesters, above all grain and cotton combines—are diesel-powered. Small gasoline-fueled farm tractors are the largest exception in this category.

Finally, mobile diesels have become indispensable in getting jetliners (powered by the other essential prime mover of modern globalized economy) off the ground. Depending on the country, between a third and two-thirds of all self-propelled ground equipment at large international airports are diesel-powered. As every observer of apron traffic knows, these vehicles include heavy pushback tractors (they are also used for moving empty jets around) that can handle planes with mass commonly exceeding 200 tons (nearly 400 t for the Boeing 747 and 560 t for the Airbus 380), large cargo loaders (used for rapid loading and unloading of containerized cargo, a key consideration for a fast ground turnaround), as well as many small baggage-cart tugs and baggage-belt loaders. But there are also less visible (or entirely hidden) diesels in air start, ground power, and air conditioning units, and most airports operate fleets of buses that transport passengers from and to planes that are not accessible by jetways.

Mobile applications of diesel engines have made great contributions to the process of economic and social globalization. Since the 1950s, the machines have also captured large shares of several stationary markets (above all, those for backup electricity generation for hospitals and businesses), for electricity needs in remote locations not connected to high-voltage lines, and for powering hydrocarbon exploration and oil and gas production offshore. For some of these applications, there are no readily available alternatives. For others, there may be other choices, but they would be prohibitively expensive. As a result, all major makers of diesel engines for mobile uses also offer stationary designs.

Electricity consumption has been increasing considerably faster than overall energy demand in both affluent and modernizing countries, and not all of this new demand can be met by large stations (thermal or hydroelectric) that transmit electricity from a central location by high-voltage lines. By far the most economical choice for generating electricity far from any existing transmission lines (including all small-island settings and offshore hydrocarbon exploration and production platforms) is to install appropriately rated diesel-powered generators. Consequently, large two-stroke, low-revolutions-per-minute (up to about 200-rpm) diesel engines have been deployed in tens of thousands of localities that are far away from any centrally supplied grid to generate electricity for a variety of local household, agricultural, and industrial uses.

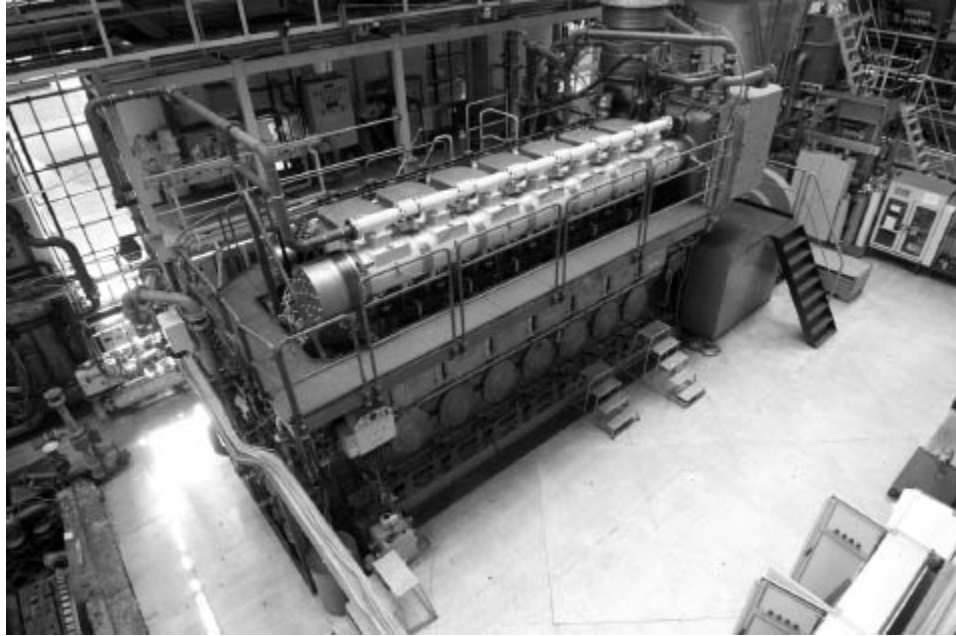
Less powerful four-stroke medium-speed (mostly 500- to 1,200-rpm) engines have been used to generate electricity at remote construction sites and pumping stations and to provide emergency backup service for hospitals, businesses (including increasingly common Internet servers), and nuclear power plants (they can be running within ten seconds of a blackout). Besides their affordable cost, this reliance on stationary diesels has four other major advantages—flexibility of size, high reliability, high efficiency, and relatively rapid installation time. Moreover, many of these plants are available in dual-fuel designs (they are able to burn inexpensive marine diesel or heavy fuel oil and also natural gas), and all larger units can be configured in an even more efficient (up to 57 percent) combined-cycle operation using the exhaust gas to heat feed water for a bottoming-cycle steam turbine.

Standardized (commonly turbocharged) designs are now available in ratings ranging from single-generation sets of a few hundred kW to complete

turn-key power plants of more than 100 MW. For example, MAN's lineup ranges from 450 kW to 18 MW for the four-stroke engines and from approximately 4 MW to about 80 MW for two-stroke machines (MAN Diesel 2008d; [fig. 5.18](#)). Typically, engines for decentralized electricity generation have ratings between 2 and 6 MW per cylinder and are offered in six- to fourteen-cylinder configurations. As a result, the total power of such installations is mostly between 10 and 80 MW. However, much larger units are available. In March 1999, Hyundai completed the world's largest diesel-powered electricity-generating plant in Chennai (in the Indian state of Tamil Nadu). Each of its four in-line twelve-cylinder 103-rpm MAN engines is rated at 51.5 MW.

Diesel-powered generating plants can be run autonomously with long spells between scheduled maintenance, and the installations that combine electricity and heat production (cogeneration) can reach overall efficiency levels of up to 95 percent. As for the installation time, small units can be operational in weeks, the sets rated at more than 100 MW could be generating within fifteen to seventeen months, and even faster deployment is available with packaged and barge-mounted units. The large stationary diesels used in the United States and European Union have also become considerably cleaner. As of January 1, 2007, the U.S. engines have to comply with lower emission levels (as a result, the new generators sold in 2007 will emit only about 20 percent nitrogen oxides compared to mid-1990s levels), and they also have to use low-sulfur diesel fuel (containing no more than 500 ppm of sulfur).





**Figure 5.18**

MAN's dual (liquid or gaseous) fuel stationary engine in a Portuguese cogeneration plant. These engines are available in nine- to eighteen-cylinder versions with power of 1 MW per cylinder for 60-Hz electricity generation at 514 rpm.

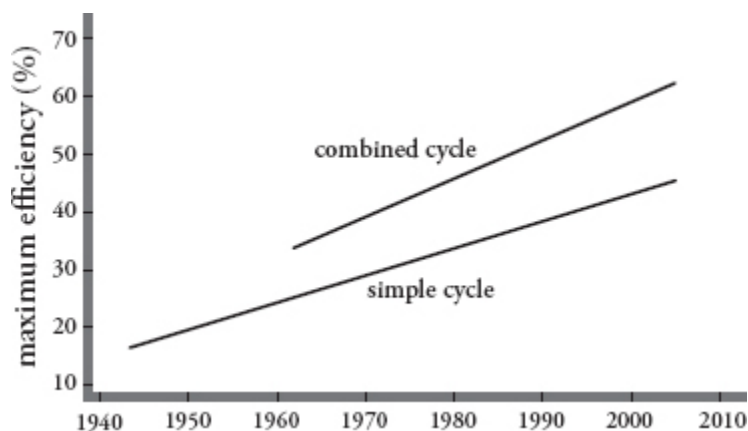
Photograph available at the MAN Diesel Web site.

Generation of electricity is by far the most important application of large stationary gas turbines. The first machine of this kind was installed by the Swiss Brown Boveri Corporation at the municipal electricity-generating station in Neuchâtel in 1939 (American Socy. of Mechanical Engineers 1988). Rated at just 15.4 MW at 3,000 rpm, its inlet temperature was only 550°C, but because nearly 75 percent of its power was used for a compressor and because it did not recover the exhausted heat, it generated merely 4 MW of electricity with very low efficiency of 17.4 percent. But the entire assembly worked reliably until the very end of the twentieth century. For the first fifteen years after the end of World War II, technical advances in stationary gas turbine design were relatively slow. By 1960, America's total annual installation reached only 240 MW. Then the pace quickened, with 840 MW installed in 1965, the year of the great November blackout in the northeastern United States, when some 30 million people were left without electricity for up to thirteen hours (U.S. Federal Power Commn. 1965).

The 1965 blackout made American utilities realize the advantages of owning natural gas-powered turbines that can be swiftly deployed in case of

emergency, and in 1968, some 4 GW of new capacity were bought, and the annual total rose to 8 GW just three years later, resulting in more than a thirtyfold rise of gas turbine power installed annually in a decade. The country's total stationary gas-turbine capacity for electricity generation rose from just 1 GW in 1963 to nearly 45 GW by 1975, but this steep gain ended thanks to the combination of high natural gas prices and sharply reduced electricity growth rates in a low-growth or stagnating economy. After the hydrocarbon prices fell from their record highs, the expansion of turbine-driven generation resumed, and by 1990, nearly half of the 15 GW of all new capacity ordered by U.S. utilities was in gas turbines (Smock 1991).

By that time, new gas-turbine installations were commonly a part of the combined cycle, an arrangement that pairs the machine with a steam turbine (Horlock 2002). Hot exhaust gases leaving the turbine contain enough energy to generate steam (that conversion takes place in a heat-recovery steam generator), and the serial coupling of a gas and steam turbine boosts the overall efficiency of electricity generation. The efficiency of stationary gas turbines rose from about 15 percent in 1940 to more than 40 percent by the year 2000 (fig. 5.19), and the efficiency of combined-cycle gas turbines (CCGTs) is calculated by adding up the performance of the two turbines and then subtracting their product. With 42 percent efficiency for a gas turbine and 31 percent efficiency for a steam turbine, it is thus possible to have a combined efficiency of 60 percent ( $0.73$  minus  $0.13$ ). Higher overall efficiencies can be also achieved by using the steam generated by a gas turbine's exhaust heat in industrial processing or in space heating, and such cogeneration (or combined heat and electricity) plants have become common in many European countries and in Japan, although not in North America.



**Figure 5.19**

The maximum efficiency of stationary gas turbines, 1940 to 2008 (based on Smil 2003).

General Electric has been the global leader in introducing increasingly more powerful and more efficient stationary gas turbines. In 1976, its first 100-MW machine had thermal efficiency of about 32 percent, and in 1990, its 150-MW turbine reached 50 percent. These advances were rapidly translated into widespread commercial use. By 1990, the worldwide orders for new gas turbines had surpassed orders for new steam turbines (Valenti 1991), and by 2000, the total capacity installed in gas turbines was slightly higher than in all fission reactors (Holmes 2001). GE's H System integrates the gas turbine, steam turbine, and heat-recovery steam generator for a combined cycle performance of 480 MW (the MS9001H) or 400 MW (the MS7001H) and an overall record efficiency of 60 percent (General Electric Power Systems 2008). In 2008, Siemens completed the world's largest gas turbine (the SGT5-8000H), a 340-MW machine that will be the primary driver of a 530-MW combined-cycle gas-turbine power plant with a net efficiency of 60 percent (Siemens 2009).

A new class of gas turbines was introduced with the commercialization of aeroderivative machines—jet engines whose design has been adapted for stationary application (Williams and Larson 1988). General Electric's first aeroderivative engine, based on the CF6 design (used by Airbuses and Boeing 747s and 767s), was the LM6000 with 40 percent efficiency (Valenti 1993), and by 2008, it offered eleven models rated from 13.7 to 49.5 MW in both a 50-Hz and a 60-Hz series (GE Aero Energy 2008). Rolls-Royce based its aeroderivative engine (rated at 51.9 MW) on its popular Trent series, and Pratt & Whitney has stationary machines derived originally from its famous JT8D engine. Some of these engines, such as Pratt & Whitney's Swiftpac, can be ordered fully assembled and packaged in multitrailer modules and are able to generate electricity capable of electricity in less than a month after arriving at their location (fig. 5.20).

Stationary gas turbines have other advantages besides their compact size and easy (ship-, barge-, or truck-borne) transportability (and hence a limited footprint and a greater flexibility of location, a particularly useful trait when installed as the prime movers on offshore drilling platforms). They are also relatively easy to maintain, can reach full power in minutes (ideal for peak-load operations), and can burn any gas as well as liquid fuels ranging from light distillates to residual oils. Their superior efficiency lowers their carbon

dioxide emissions and does away with any need for external cooling, proper silencers keep their noise below 60 decibels adjusted at a distance of 100 m, and (at greater than 500°C) exhaust can be used as a source of industrial processing heat. And they are an excellent investment, as their capital cost is lower than that of steam-turbine generation.



**Figure 5.20**

Pratt & Whitney's Swiftpac provides quick (installed in less than a month) and reliable naturalgas-powered electricity generation in power plants of approximately 30 or 60 MW.

Photograph available at Pratt & Whitney's Web site.

At least one other application of stationary gas turbines must be noted in the context of economic globalization. Natural gas has emerged of a leading fuel of this new economic era, and I have already noted the role that has been played by massive marine diesels in enabling a global liquefied natural gas trade. Terrestrial transport of natural gas in large-diameter pipelines benefits from the efficiency, reliability, and low cost of the gas turbines that are used to drive compressors that are located at regular intervals along pipeline routes. Now the longest export pipeline—which is carrying natural gas from western Siberia to western Europe—has forty-one stations along its nearly 4,500-km route. Smaller-diameter lines use turbines of just 1 to 15 MW, but aeroderivative units in excess of 30 MW have been installed since the 1990s (Wilson and Baumgartner 1999).

Finally, gas turbines have begun to encroach on a realm that was previously dominated by diesel engines. After being used by naval vessels, hydrofoils, and hovercrafts, aeroderivative gas turbines have also found a new niche in powering passenger ships, and their low noise, low emissions, and lack of vibration make them particularly suitable for large cruise ships. A much advertised choice in this field was the installation of two GE LM2500+ aeroderivative gas-turbine generator sets (approximately 30 MW each) in combination with four diesel generators to power the RMS *Queen Mary 2* in 2004 (GE Aviation 2004).

# 6

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## Benefits and Costs

Diesel blieb sein Leben lang überzeugt dass die Zukunft unerhörte soziale Erschütterungen bringen würde. Zu mir sagte er oft: “Du wirst es erleben. Du wirst es erleben!”

[All his life, Diesel remained convinced that the future would bring unheard of social shocks. He told me often: “You will experience it. You will experience it.”]

—Eugen Diesel recalling conversations with his father

Neither diesel engines nor gas turbines were invented to fill some waiting market niches. Although Diesel had a particular market in mind for his new efficient engine (small manufacturers who could not afford a steam engine), that market soon found that electric motors were a more affordable, more reliable, more flexible, and easier-to-use choice for an overwhelming number of applications. Whittle’s and von Ohain’s motivation was simply to design a better and, above all, a faster propulsion for airplanes. In both cases, during the earliest stages of developing their inventions, only the inventors themselves and a few of their early supporters were enthusiastic about the eventual commercial prospects of their innovations. The development of initial designs into marketable machines was met in both cases with a highly critical reception by some leading experts and business executives.

Fortuitously, the commercial maturity of both engines coincided almost perfectly with the post–World War II emergence of new, much more open economic structures that were promoted first by the United States in its relations with the Western Europe and Japan and later by a worldwide progress toward freer trade. It would be difficult to argue that in the earliest stages of their commercial diffusion, the two prime movers were stimulated primarily by their inventors’ expectations for eventually huge financial payoffs. But there can be no doubt that the anticipated needs and promising profits of international trade and travel have been among a few key factors

that have helped to explain the sustained and impressive technical advances in the performance and commercial use of the two prime movers.

As the engines found new and rapidly expanding niches in an increasingly interconnected world that had a rising demand for the long-distance transport of goods and for personal travel, their widespread deployment created strong incentives for further enhancement of their capacities and efficiencies as well for their more durable and safer performance. Such positive feedback would have mattered much less in the more autarkic pre–World War II world or in the absence of decades-long rapid postwar economic growth in the Western world. More recently, a key stimulus was provided by Deng Xiaoping’s economic reforms, which lifted China from its Maoist misery and made it into the world’s workshop. It needs enormous inputs of raw and semifinished materials to supply the global market with labor-intensive manufactures and increasingly with higher-quality goods.

Many nontechnical factors of the past two generations have coalesced to stimulate the technical progress of the two prime movers. These include the guarantee of safe shipping routes provided by U.S. naval power, rising disposable incomes in North America, the newly reconstructed economies of Japan and Western Europe, steadily broadening international trade agreements (culminating in many free-trade accords), and capital flows to China’s policy of trade-driven economic growth. The globalization of trade and travel and the post-1950 development of diesel and jet engines have thus constituted a reciprocal and complementary process.

There have been no obvious, technically deterministic causal arrows. The commercialization of the two prime movers did not engender economic globalization (as I note in [chapter 1](#), its origins long predate their invention), and their greater capacities and improved performance were not the key drivers of the intensified post-1950 globalization that has been driven by a multitude of synergistic stimuli. But as Aristotle put it in his *Metaphysics*, “the things best to know are first principles and causes. For through them and from them all other things may be known.” Without prime movers, all technical advances in designing and building better means of transportation and all organizational, managerial, and transactional improvements aimed at the intensification of international trade would remain just interesting unrealized concepts. And with less capable and less efficient prime movers, economic globalization could not

have scaled its current heights at anywhere near its reach, cost, and efficacy. So in this Aristotelian perspective, it seems natural to see these two remarkable machines playing *primae inter pares* roles on the crowded and complex stage of economic globalization (although, undoubtedly, some historians of technical advances would argue that modern telecommunications have been the key inventions that have made today's globalization possible).

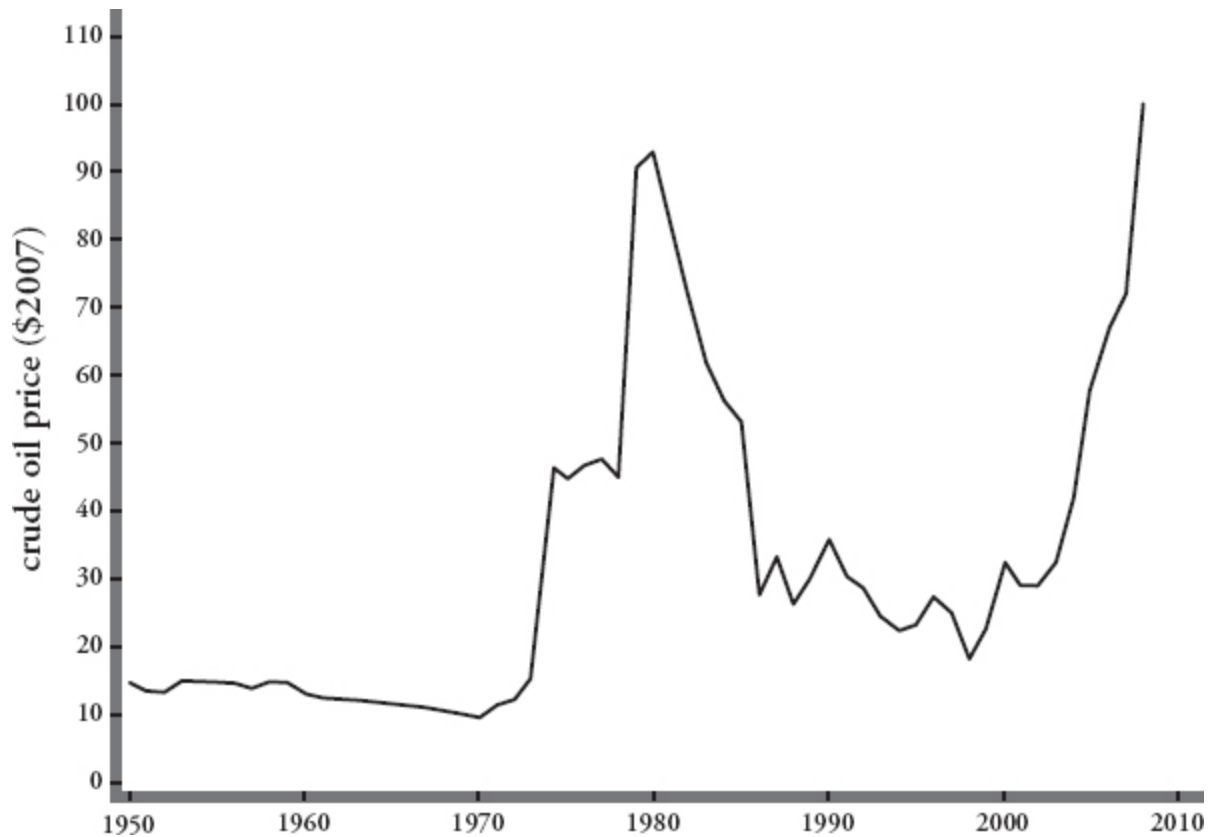
As an inevitable result, the two prime movers have had many obvious (as well as some not so commonly appreciated) impacts on the global economic integration, on the unprecedented growth of modernizing economies, and on the maintenance of an affluent life style in high-income countries. It is no exaggeration to conclude that diesel engines and gas turbines have helped, in no small measure, to change the course of modern history. The two most obvious effects have been the enormous increase in the mass of all internationally traded raw materials and finished goods and the number of intercontinental travelers. Both of these trends have intensified thanks to the reinforcing feedbacks of rising volumes and declining unit costs. Those feedbacks have lowered shipping costs to such an extent that distance to the market has been largely eliminated as a concern in locating manufactures or selecting the origin of imported minerals, food, and other raw materials and pursuing lucrative export markets.

Inexplicably, this is not a universally accepted conclusion. For example, in his review of three recent books on containerization, Roland (2007, 391) maintains that "countries still trade most with their neighbours, suggesting that declining transportation costs have not banished distance." This is arguing against incontrovertible evidence. In 2007, the world's largest economy took only 26 percent of its imports from its Canadian and Mexican neighbors, and hence nearly three-quarters came from other continents. Similarly, less than 20 percent of all Japanese imports originated in China and Russia (Japan's largest neighboring continental economies), while China's imports from its two powerful neighbors, Russia and Japan, added to only 16 percent of the total (World Trade Organization 2008). Not surprisingly, only the European Union countries are strong neighborly traders (with 65 percent of imports coming from other EU members).

There can be no doubt that the role of distance is much reduced in modern economic decision making, and the progressively lower unit costs of long-distance transportation have been predicated on the rising capacities



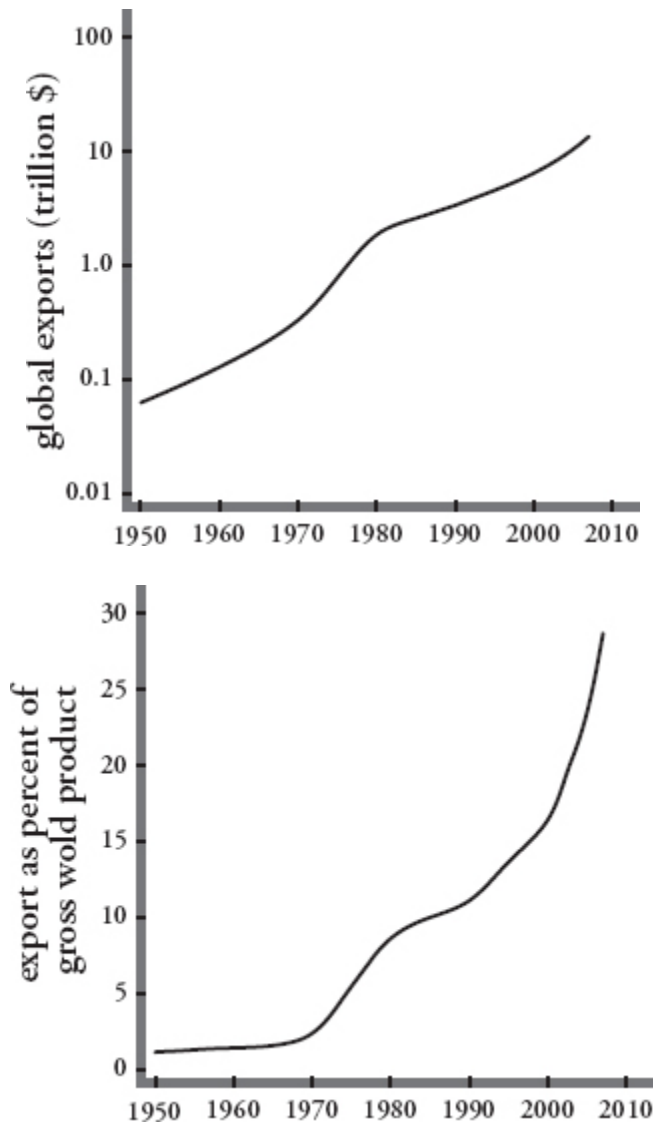
and improving performances of the two prime movers and the machines they power and also on the relatively low costs of the energies they use. The post-1950 diffusion of the two prime movers was greatly helped by very low pre-1973 energy prices (fig. 6.1). The high prices that prevailed between 1974 and 1985 slowed down the expansion process, but intervening technical advances and higher conversion efficiencies led to a new, generation-long spell of cheap energy (1986 to 2006), creating conditions that were almost as favorable as those in the 1960s. Conversely, as crude-oil price almost tripled between 2005 and the summer of 2008 (it averaged just over \$50/barrel in 2005 and reached nearly \$150/barrel in July 2008), the rise brought fears about the end of a globalization fueled by cheap energy. But as the price collapsed to well below \$50/barrel by the end of 2008, those fears were displaced by concerns about the depth and duration of the most serious post-World War II global economic recession. Very high oil prices can return, and economic globalization is undoubtedly reversible (not entirely but to a significant degree). After all, it has been only recently that for the first time in history, international trade has begun to make a truly global difference. There is nothing new about imports from distant places. Spices from India, silk from China, and goods from East Africa were readily available in early imperial Rome, and (as is noted in chapter 1), ownership of many exotic imported items was comparatively common among middle- and upper-income people Western Europeans in the early modern era. But the overall volume and value of this trade remained globally insignificant until after World War II.



**Figure 6.1**

Oil prices, annual average, 1950 to 2008 (plotted from data in British Petroleum 2008 EIA 2009b).

World merchandise exports added up to less than \$60 billion in 1948 and were less than \$160 billion fifteen years later. But by 1983, they rose to \$1.8 trillion, twenty years later they were nearly \$7.4 trillion, and by growing nearly 85 percent in just four years they reached \$13.6 trillion in 2007 (WTO 2008; [fig. 6.2](#)). In 1950, these exports amounted to just 1 percent of gross world product (GWP), and by 1975, their share was almost 6 percent. But by 2000, it reached 16 percent; by 2005, it was just over 23 percent; and by 2007, it approached 29 percent. More than a quarter (but not quite yet a third) of the world's wealth is thus being created by international trade. When measured by mass, more than 80 percent of this trade is carried by ocean-going ships, while in value terms about 35 percent of it was moved by airplanes in 2007 (Intl. Air Transport Assn. 2009). The rest of the merchandise, whether by volume or by values, is moved mostly by diesel-powered trains, barges, and trucks on international routes. I doubt that anything can summarize better the importance of the two prime movers for the prosperity of the global economy than these figures.



**Figure 6.2**

Global merchandise exports and their share of the world economic product, 1950 to 2007 (calculated and plotted from data in World Trade Organization 2008 and World Bank 2008).

International seaborne trade involves more than fifty thousand vessels belonging to some ten thousand shipping companies, and in mass terms it grew from nearly 2.6 Gt in 1970, 3.7 Gt by 1980, and 4.0 Gt by 1990, but it jumped to almost exactly 6 Gt by 2000 and surpassed 8 Gt in 2007 (U.N. Commn. for Trade and Development 2008). To give some comparative yardsticks, annual global oil extraction now amounts to 4 Gt, and annual harvest of cereal grains is about 1.6 Gt. International seaborne shipping moves annually a mass twice as large as that of all produced crude oil and five times as large as that of all harvested cereals. Crude-oil and refined-oil

products are a third of this total (2.681 Gt in 2007), main bulk dry cargo (iron ore, coal, bauxite, alumina, phosphates, and grain) accounts for a quarter (1.997 Gt in 2007), and the rest (3.344 Gt in 2007) is other dry cargo now carried largely in containers.

The shares are somewhat different when the comparisons are done in tkm. Crude oil and refined products accounted for about 38 percent in 2007, five main dry bulk cargoes accounted for 33 percent, and other dry cargoes added up to 30 percent. In monetary terms, this seaborne trade surpassed \$10 trillion a year. The regional origin of ship cargoes reflects the dominance of the Middle Eastern (that is, West Asian) dominance of crude oil exports (nearly 45 percent of crude shipments originate there), and the still substantial gap between the merchandise exports of affluent and modernizing economies. In 2007, the former, with less than 20 percent of the world's population, accounted for 40 percent of all loaded dry cargoes. Affluent countries have also benefited disproportionately from the remarkable economies of scale that have resulted in the cost of shipping rising only at about a tenth of the overall inflation rate. As a result, transportation costs are negligible shares of retail prices, typically amounting to less than 1 percent for many bulk products and rarely more than 1 to 2 percent for manufactured items.

Seaborne shipping is the least expensive mode of transportation—because of the large capacities of the vessels, the highly mechanized ways of loading and unloading bulk cargoes and containerized merchandise, and the energy efficiency of the diesel engines (diesel is by far the most energy-efficient means of long-distance transportation). Specifics vary with vessel sizes and shipping speeds, but when the comparisons are done in terms of energy use per tkm, large vessels use an order of magnitude less energy than railways and two orders of magnitude less than large long-haul trucks. Supertankers consume less than 50 kJ/tkm compared to 300 to 600 kJ/tkm for railways. Smaller but faster ships need between 100 and 150 kJ/tkm, and heavy trucks need mostly between 2 and 4 MJ/tkm.

As for air cargo, its global aggregate has seen a much steeper growth than international shipping. During the last twenty years of the twentieth century, the mass of seaborne trade rose roughly 1.6 times, but the mass of air cargo nearly tripled. There is an enormous difference in absolute numbers: air global air cargo total rose from about 10 Mt in 1980, to about 30 Mt by 2000, and to about 42 Mt by 2007 (Intl. Civil Aviation Organization 2006;

Intl. Air Transport Assn. 2009). The respective totals for seaborne cargo were roughly 3.7, 6.0, and 8 Gt, the last total being 190 times larger than the mass of the airborne merchandise. And the difference is even greater when the comparison is done in tons per kilometer. In 2007, the maritime total was 60.9 trillion tkm, and the air cargo aggregate was 193 billion tkm, a 315-fold difference (Boeing 2008b). But as already noted, the comparison is different in value terms, as only very valuable or highly perishable merchandise is sent by air.

This new web of economic integration that has been created by intensifying international trade has brought considerable rewards to both long-established exporters and newcomers. Germany, a leading pre-World War II exporter, has been able to hold its disproportionately high share of global exports (around 10 percent) since the early 1950s, and in 2006 it surpassed the United States (with \$1.11 trillion versus \$1.04 trillion) to become the world's largest exporter of merchandise (WTO 2008). Among the newcomers, global trade brought immense benefits first to Japan (beginning in the 1950s and culminating in the 1980s), then to smaller East Asian economies (South Korea, Taiwan, and Hong Kong), and since the early 1990s, it has been the key factor behind the rise of China, the world's new manufacturing superpower, as well as behind the reinvigorated growth in India. Between 1983 and 2007, China's exports grew from about \$22 billion to \$1.2 trillion, a 55-fold increase, and India's exports rose from less than \$10 billion to about \$150 billion, a 16-fold expansion (WTO 2008).

These expansions have played a major role in lifting some 200 million Chinese from poverty, in raising China's per capita GDP (in purchasing power parity) to above \$4,000 (comparable to that of Syria) and India's rate to about \$2,200 by the year 2005 (World Bank 2009). In China's case, they have also led to a record-breaking increase in foreign reserves and to the emergence of China as the largest foreign holder of U.S. Treasury bills. By August 2009 China held nearly \$800 billion of the nearly \$3.5 trillion that was in foreign possession, followed closely by Japan, with the United Kingdom in distant third place (Federal Reserve Board 2009).

New sources of overseas demand and new export opportunities also benefited all countries that were endowed with mineral resources or with major food-production capabilities. The oil-rich nations of the Organization of the Petroleum Exporting Countries are not the only notable example of the first kind of exports. Russia has realized great gains from its sales of oil

and natural gas to Europe (as has Norway), and Australia, Brazil, and Chile have become the major suppliers of coal and mineral ores to China. Brazil, the United States, Canada, and Argentina have been the major beneficiaries of greatly expanded food exports. At the same time, a mass influx of inexpensive (but increasingly high-quality) consumer goods has benefited the importing countries, above all by keeping inflation in check for nearly a generation.

As always, there is an obverse to any large-scale, complex set of arrangements or to any powerful trends. The economic globalization that has been impressively enabled by the two prime movers has also had many indisputably negative effects. Few concerns have been more important than the large job losses in diverse manufacturing industries in countries that have become increasingly dependent on imports. This effect (which often is highly emotionally perceived) is perhaps best exemplified by the dependence of America's Wal-Mart, the world's largest retailer, on China's manufactures and by the concurrent loss of manufacturing jobs in the United States. The best estimate is that in 2006 Wal-Mart sourced at least 80 percent of its worldwide sales from China (with virtually all of these products shipped in containers) and that these imports have displaced nearly 200,000 U.S. jobs (Scott 2007). The overall American job loss attributable to all Chinese imports is much less easy to determine.

In addition to contested economic impacts, there also have been various (and much less controversial) environmental concerns accompanying the process of globalization. Emissions from diesel-powered trucks have been a long-standing concern, but stricter regulations have greatly reduced their impact, and the latest innovation (the injection of urea into the exhaust stream to scrub nitrogen oxide is already common in Europe and is starting in the United States in 2010) will make large road diesels even more acceptable. The increased concerns about the potential pace of global warming have brought attention to greenhouse-gas emissions from ships and aircraft. Although maritime shipments have the lowest carbon dioxide emission rates when compared to other modes of cargo traffic in terms of grams per ton per kilometer, in aggregate the industry is a major consumer of low-quality fuels and hence a comparatively large emitter. The International Maritime Organization's first study of carbon dioxide emissions from maritime shipping was based on the consumption of 138 Mt of bunker fuel in 1996 (30 Mt of distillates and 100 Mt of residual fuel) and

put them at about 440 Mt, just 1.8 percent of that year's global total (Intl. Maritime Organization 2000).

Since that time, there has been a significant expansion of the world's maritime traffic. By 2008, it increased by 60 percent in terms of tkm, but containerized shipping (by far the highest consumer of fuel due to its high speeds) expanded roughly 3.5-fold (UNCTAD 2008). By 2008, total annual fuel consumption in ocean shipping reached about 370 Mt (equivalent to nearly 10 percent of the world's oil consumption, with about 250 Mt of that grand total being residual oil), releasing nearly 1.2 Gt of carbon dioxide or about 4 percent of global emissions of the gas originating in fossil-fuel combustion (Energy Information Admin. 2009a). Compared to national totals, these emissions would make the maritime traffic as large a source of carbon dioxide as Japan or India.

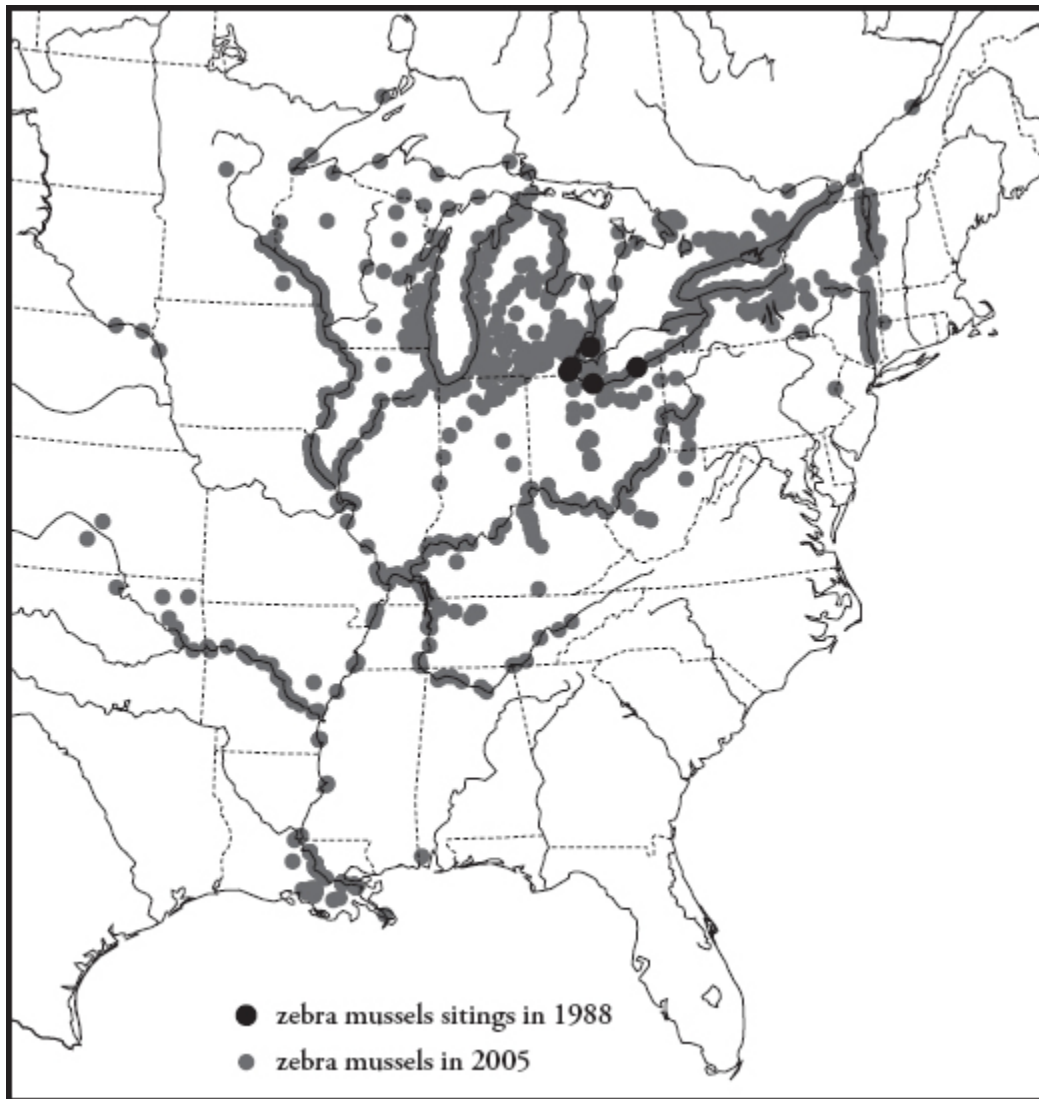
The combustion of low-quality bunker fuels (containing commonly between 2 and 3 percent sulfur, with as much as 4.5 percent permissible according to the International Maritime Organization regulations) is also a relatively large source of sulfur dioxide. In 2008, emissions were at least 14 to 15 Mt of the gas, amounting to as much as 8 percent of all anthropogenic sulfur emissions. Moreover, most of these acidifying emissions are released into otherwise pristine air over the northern Atlantic, northern Pacific, and northern Indian Ocean. As with all high-temperature combustion, maritime shipping is also an important source of nitrogen oxide emissions (at least 25 Mt in 2008, or roughly a quarter of the anthropogenic total from the combustion of fossil fuels) and volatile organic compounds. Nitrogen oxides and volatile organics (also released by the evaporation of crude oil and oil product tanker cargo) are two key ingredients of the complex photochemical reactions that lead to the production of undesirable tropospheric ozone, which is both a potent greenhouse gas and a key constituent of photochemical smog.

In addition to concerns about air pollution and changes in the earth's radiation balance, there are also the ever-present risks of the global spread of microbes and invertebrate species in the ballast water of commercial ships (Ruiz et al. 2000; Intl. Maritime Organization 2008) and worries about the accelerated transmission of infectious diseases by international air traffic. Ships on international routes transfer annually at least 3 Gt and perhaps as much as 5 Gt of ballast water, which is estimated to contain at least seven thousand different aquatic species (IMO 2008). Some of these

shipborne bioinvasions can devastate invaded aquatic ecosystems and are very difficult to control and impossible to predict. Zebra mussels were carried in European ships' ballast water to North America for generations, but once they took hold in Ohio and Michigan in 1988, they spread rapidly and are now present in all of the Great Lakes and throughout most of the Mississippi basin (fig. 6.3). Their massive colonies cover underwater structures, obstruct pipe inlets, reduce the presence of native mussel species, and cause economic damage that has been estimated at billions of dollars per decade (U.S. Geological Survey 2000).

Eliminating all discharges of ballast water would be a perfect solution to waterborne invasions, but this is practical only for container ships that carry cargo on every leg of their route and not for oil and LNG carriers, which return from their destinations with empty holds. Other invaders can be carried in dry cargo. A notable example is the Asian longhorned beetle (*Anoplophora glabripennis*), a most unwelcome recent introduction to North America from Asia that has been carried in wooden packing crates from China (Peterson, Scachetti-Pereira, and Hargrove 2004). Cutting down trees that have been infested with this beetle is the only known defense against its spread. Invasive species can be also carried by aircraft. Brown snakes (*Boiga irregularis*) can be carried in the wheel wells of large jetliners or in air cargo from Guam (where their shipborne introduction has virtually destroyed the island's small vertebrates and song birds and caused enormous damage to electric wiring) to other Pacific islands (Fritts and Leasman-Tanner 2001).





**Figure 6.3**

The diffusion of zebra mussels in eastern North America, 1988 to 2005 (based on U.S. Geological Survey 2009).

I address additional specifics of these economic benefits, environmental problems, energy demand, strategic considerations, social implications, and political reactions in detail as I review the effects that the two prime movers have had on the expansion of the global trade in bulk commodities (dominated, in mass terms, by shipments of crude-oil and refined-oil products and by exports of iron ore), the intercontinental shipping of manufactured goods in container vessels (now the principal mode of exporting every imaginable industrial product and, increasingly, high-value

agricultural commodities), and flights on a planetary scale (including long-distance freight deliveries).

### **The Expansion of Global Trade: Bulk Commodities**

Bulk cargo is any loose homogeneous commodity that is loaded without any packaging directly into a vessel's hold simply by gravity. Wet-bulk carriers are loaded most frequently with crude oil, refined-oil products, liquefied natural gas, and a variety of chemicals (but also with wine and orange juice). Dry-bulk carriers are readily identifiable by large hatch covers that are lifted or rolled away to load the massive holds. Their most voluminous cargoes are metallic ores (iron ore and bauxite), coal, cement, and grain. The long-distance transport of bulk commodities is a textbook example of economies of scale, and the world's most widely traded liquid offers the most consequential example of the effect, as international shipments of crude oil carried by large tankers (powered exclusively by massive diesel engines) have recorded an order of magnitude increase in just two generations (Ratcliffe 1985; Spyrou 2000).

Oil was initially transported in barrels (bbl, from the original *blue barrel*, the standard container of 42 U.S. gallons or 0.159 cubic meters) by general cargo ships, which is an expensive mode of shipping. The first true tanker (the British-built *Glückauf*) was a vessel of just 300 tons that was launched in 1884, but during the following year, 99 percent of U.S. oil exports were still shipped in barrels. Just before World War I (when the United States was by far the world's largest oil producer and when the only other important suppliers included Russia, Romania, Burma, and Indonesia), shipments of petroleum and its refined products amounted still to a small fraction of the overall extraction and were carried by a fleet of steam-engine-powered tankers with capacities of 4,000 to 5,000 dwt. The *John D. Archbold*, a 22,000-dwt tanker built in 1921, remained the record-sized vessel for nearly thirty years.

In the 1930s, typical ships still carried only about 10,000 t and this slow growth was hardly surprising. Before World War II, the United States, the world's largest oil consumer, was also the world's largest oil producer. Oil imports by the coal-dominated economies of Europe and Japan remained small, and the largest Middle Eastern oilfields were yet to be discovered. In contrast, the post-1945 growth of tanker capacities was very rapid. The first

phase of postwar exports was carried by surplus T-2 tankers: 620 of these vessels, powered by 4.5-MW steam turbines and electric drives, were built between 1942 and 1946 for the war effort, and their capacity was 16,765 dwt (T2tanker 2009). After that, sizes began to rise so fast that the *supertanker* designation, which before the mid-1950s was applied to vessels of 50,000 dwt, shifted by 1959 to ships of 100,000 dwt (the *Universe Apollo* was the first tanker of that size) and then to 200,000 dwt ships. In 1966, Ishikawajima-Harima Heavy Industries completed the record-sized 150,000 dwt *Tokyo Maru* and later in the same year the 210,000 dwt *Idemitsu Maru*.

By 1973 (at the time of the first round of OPEC-driven oil-price increases), there were 366 very-large crude carriers (VLCCs) and ultra-large crude carriers (ULCCs), with the largest vessels in excess of 300,000 dwt (Kumar 2004), and it seemed natural to expect ships in excess of 500,000 dwt. The shipping company owned by Aristotle Onassis considered constructing a segmented vessel that was capable of carrying 1 million dwt. But only one tanker with capacity in excess of 500,000 dwt was ever built: the *Seawise Giant* was launched in 1975, enlarged three years later, and operated first in the Gulf of Mexico and then in the Persian Gulf. The ship was hit by a missile in 1986 during Iran-Iraq war and was subsequently relaunched as the 564,650 dwt (nearly 459 m long and with draft of 26.4 m) *Happy Giant*, soon renamed *Jahre Viking*, eventually sold and renamed once more as the *Knock Nevis*. It is now a floating storage and offloading platform in the al-Shahīn oilfield in Qatar (Knock Nevis 2008).

Supertankers did not stop increasing because of any insuperable technical difficulties in building larger vessels or because their propulsion requirements would exceed the capacities of the largest diesel engines. Today's largest container vessels have diesel engines that are nearly three times as powerful as those propelling even the largest ULCCs. The combination of diminishing returns in building larger vessel and increasing risks in operating them put an end to tanker growth (fig. 6.4). Reliance on very large carriers has kept unit costs low. In 2006 and 2007, it cost only about 40 percent as much to build a 300,000-dwt carrier as it did to construct a 45,000-dwt vessel, and the operating costs differential is very similar (UNCTAD 2008). As with all economies of scale, however, there have been diminishing returns. The Japanese showed a long time ago that doubling size from 60,000 to 120,000 dwt cut the building cost by 30

percent, doubling to 240,000 dwt brought an additional cost of only about 15 percent, and going much above 300,000 dwt might be counterproductive once other considerations are factored in (Izuta 1967).

All very large ships are more difficult to maneuver in constrained passages or during docking, and they have to navigate carefully in waters where their draft (15 to 24 m for fully loaded VLCCs and ULCCs) leaves little room to spare. Their momentum requires long distances before they can be stopped in emergency, while fears of accidental oil spills and the ensuing destruction of marine and coastal life have raised insurance premiums and brought new rules demanding universal double-hull construction. Inevitably, their operational flexibility is diminished (as they can moor at only a handful of the world's deepest ports and cannot be readily dispatched to other destinations), and the largest vessels also present greater security concerns as they have to pass through some potentially dangerous traffic choke-points (Energy Information Admin. 2005).



**Figure 6.4**

The *Ice Explorer* in the Pacific leaving Japan. It is a 150,000-deadweight tonnage, 274-meter-long, very-large crude carrier built in 2006.

Photograph is available on the MAN Diesel Web site.

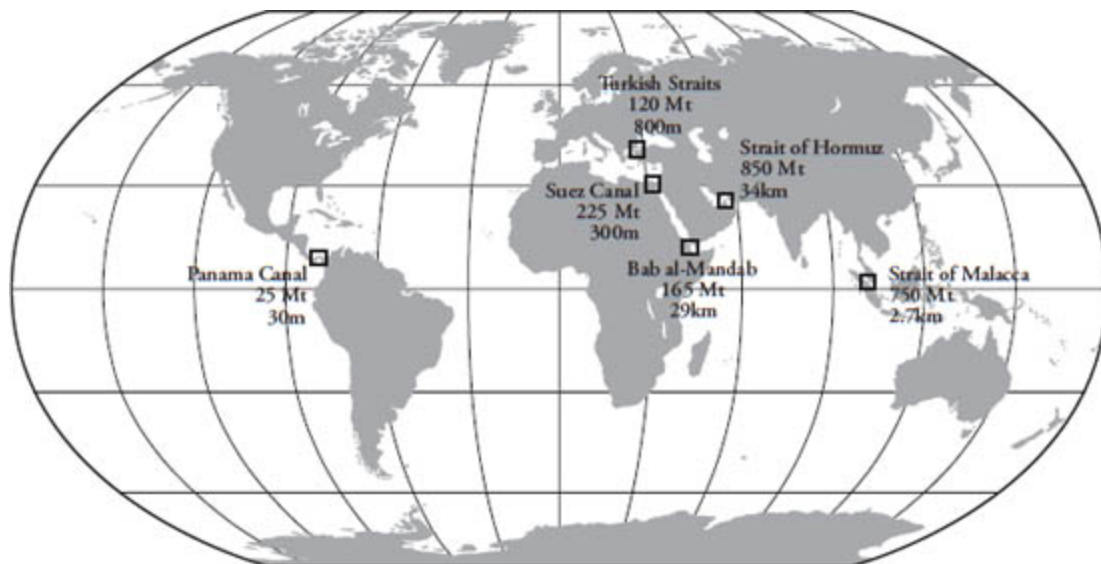
Perhaps the best news regarding all of these concerns has been a much reduced frequency and magnitude of accidental oil spills. The International Tanker Owners Pollution Federation (ITOPF) has maintained a detailed database of all oil spills from tankers since 1974, and the data show welcome progress in both the number and volume of such accidents. During the 1970s, the annual mean was twenty-five spills over 700 t; during the 1980s, the rate fell below ten spills (9.3); during the 1990s, it averaged 7.8 spills; and since 2000, it has been below five (ITOPF 2009). As for the magnitude of accidents, the largest event since 2000 was the 2002 spill of 63,000 t by the *Prestige*, while the previous records were 260,000 t by the *ABT Summer* in 1991, 252,000 t by the *Castillo de Belver* in 1983, and 287,000 t by the *Atlantic Empress* in 1978. New regulations requiring all new tankers to be double-hulled will further reduce both the frequency of accidental oil spills and their average volume. This means that nonaccidental discharges from ships (above all, those of fuel-oil sludge) have become a more important source of pollution than accidental spills.

At the same time, concerns about the security of tanker passage through three major chokepoints have intensified because of the rise of Iranian ambitions and a large increase in Somali pirate attacks. Iranian actions could easily block the Strait of Hormuz, through which some 40 percent of all seaborne oil moves to the market, and Somali pirates have become increasingly active in the Western Indian Ocean, including the straits of Bāb al-Mandāb, through which oil tankers must pass on their way the Red Sea and the Suez Canal (fig. 6.5). In November 2008, the Somali pirates seized a VLCC, the 318,000-dwt *Sirius Star*, which was transporting oil for Aramco (a Saudi-owned company). This was the largest vessel ever hijacked. After an initial demand for a ransom of \$25 million, the pirates eventually released the vessel after receiving \$3 million.

Piracy (albeit not with such high frequency as in the seas off Somalia) has been also a problem in the Straits of Malacca, which are frequented by nearly all tankers taking Middle Eastern oil to China, Taiwan, South Korea, and Japan. As preventive patrolling by navies of the concerned states can never eliminate the piracy threat over such vast areas of ocean, defensive countermeasures are perhaps the best way to minimize the chances that a vessel will be seized and that a large ransom will have to be paid for the release of its cargo and crew (Greenberg 2006). Another security consideration for the global oil trade is the existence of some extremely

large loading terminals (such as Saudi Arabia's Rās Tanūra, Kuwait's Mīna al-Ahmadī, Iran's Kharg Island, and Iraq's Mīna al-Bakr) and off-loading ports (such as Rotterdam, Kagoshima, and Houston).

Disruptions in their operation by terrorist attacks would bring an instant spike in world oil prices, and the minimization of these risks leads to more spending on protecting these installations (particularly in the Saudi case) and adds to other compelling arguments against a high level of dependence on imported crude. At the same time, unlike the energy-rich United States (whose large imports are primarily the function of excessive consumption; the country remains the world's third largest producer of crude oil), many resource-poor nations have no other alternative. But even concerns about rising construction costs for ever-larger carriers, restrictions imposed by their size, oil spills, and the security of large oil terminals and major shipping lanes have not prevented the rapid and extensive expansion of international oil shipments.



**Figure 6.5**

The principal chokepoints of shipborne crude oil exports and the approximate tonnage that passed through them in 2007 (numbers rounded from British Petroleum 2008).

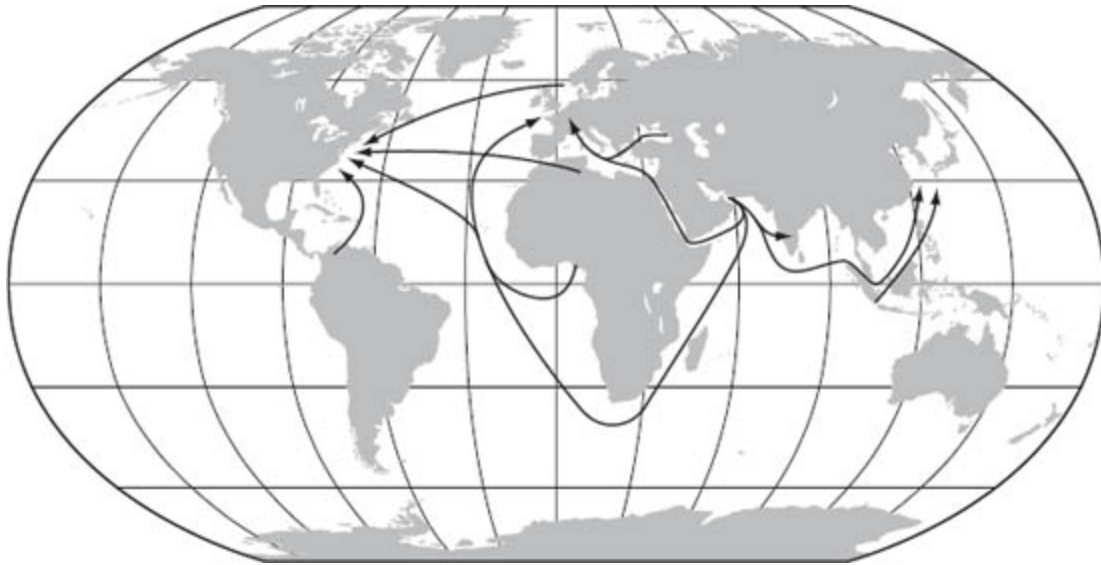
The industry's dual growth (of individual vessel capacities and of the total mass of cargo moved annually) has been driven by two key factors—by the need to cope with steadily increasing volumes of oil entering intercontinental trade (and later also increasing shipments of refined products) and by the quest for lower transportation costs. The total volume



of internationally traded crude oil (moved by tankers or pipelines) rose from just 140 Mt in 1950 to just over 1.5 Gt by 1975 and to 2.7 Gt by 2007 (U.N. Organization 1976; British Petroleum 2008), when nearly fifty oil-producing countries were selling crude oil to more than 140 nations. The United States, the world's largest importer of liquid fuels, now sources its purchases of crude oil and refined products from seventy countries on four continents, although all of the imports from Canada, its largest supplier, come through pipelines (Energy Information Admin. 2007b).

Worldwide tanker shipments of crude-oil and refined-oil products reached 1.86 Gt by 2007 (UNCTAD 2008), with the most massive interregional transfers originating in the Middle East and destined primarily for East Asia, Europe, and the United States. Other key sources of shipborne crude oil are Russia, Southeast Asia, North and West Africa, and Central and South America (fig. 6.6). Shipments of refined products have been expanding even faster, from about 110 Mt in 1950 to 360 Mt by 1970, and they equaled about 815 Mt by 2007. The mass of shipped liquid fuels was, at about 2.7 Gt/year, nearly double the 1970 total, and it was equal to roughly 33 percent of the tonnage of all goods shipped that year. Almost 90 percent of all crude-oil and refined-oil products are now carried in vessels larger than 50,000 dwt, and in 2008, the world tanker fleet comprised some 4,800 ships with an aggregate capacity of nearly 400 million dwt with VLCCs (240,000 to 350,000 dwt) accounting for roughly 40 percent of the total (UNCTAD 2008).

Their large carrying capacity and their inexpensive and reliable propulsion by diesel engines have lowered shipping costs to such an extent that the distance from a seller to a final market has been essentially eliminated as an important consideration in buying crude oil. A delivery from another continent has become as affordable as (and often more convenient than) procurement from a neighboring country. Freight rates for large tankers tend to fluctuate considerably with changing demand. For example, spot rates for 275,000-dwt vessels from the Arabian Gulf to Europe averaged about \$83,000/day in 2004 and only \$44,000/day in 2007. The rate was about \$120,000/day in May 2008 but half that rate just five months later (Tanker Freight Forecaster 2008).



**Figure 6.6**

Major interregional shipments of crude oil (plotted from data in British Petroleum 2008).

But even with a spot freight rate at \$100,000/day and with oil prices at just \$50/barrel, the transport of crude oil from the Middle East to Europe by a VLCC would equal less than 2 percent of the cargo's value. Lower long-term freight rates, larger cargoes, and shorter shipping distances can push that rate to less than 1 percent of the cargo's total value. And relative energy costs are similarly low. A 300,000-dwt VLCC moving Saudi oil to the United States needs an equivalent of only about 0.7 percent of the fuel that it carries to power its large diesel engines on the trip of just over 20,000 km if going from Rūs Tanūra Ras around Africa to Houston. Even the considerably higher costs of the liquid fuel that is used by massive marine engines or a doubling on long-term freight rates would have a much smaller impact on the total cost of refined-oil products than do the costs of oil production and refining and the level of taxation imposed by the governments in oil-importing countries.

Perhaps in no other case of modern global trade is there less need for stressing the overall importance and truly transformational nature of an activity than in the case of tanker-borne oil (and refined-oil product) exports. Numerous aspects of this complex phenomenon and its economic, political, and strategic consequences have been receiving close (and possibly even excessive) coverage ever since the first round of the OPEC-driven quintupling of world oil prices in 1973 and 1974 (Smil 2008). The key concerns have included high levels of dependence on imports from the



OPEC producers among virtually all affluent nations (Canada and Norway being the only self-sufficient rich countries), economic dislocations arising from these large money transfers, the role of oil earnings in fostering strategic ambitions and supporting terrorism (Iran being the best example on both counts), and worries about an imminent peak of global oil production.

When these perspectives are included, the benefits and advantages of a relatively inexpensive, easy-to-transport, easy-to-store, convenient, and flexible high-energy-density liquid fuel—whose use has revolutionized every mode of land and water transportation and made flight possible—look questionable. Could it be argued that diesel engines—prime movers of unprecedented low cost, high efficiency, and admirable reliability—helped to launch and to intensify a phenomenon of excessive energy use and unsustainable dependence on a highly unevenly distributed resource whose affordable worldwide availability would not be otherwise possible? Optimists (or technoenthusiasts) may point out that, even if some more pessimistic scenarios about an early peak of global oil extraction were correct, diesel engines already play a key role in creating the global market for natural gas, a fossil fuel that is even more abundantly present in the earth's crust and that will be a major substitute (directly or after conversion to liquids) for refined-oil products.

Natural gas is the cleanest of all fossil fuels, and in many ways it is also the most convenient and most efficient to use—whether in household furnaces, large industrial boilers, or stationary gas turbines. The gas is usually at least 90 percent methane, with small amounts of ethane and propane and trace quantities of water, nitrogen, oxygen, carbon dioxide, and sulfur, all of them relatively easy to separate from the gas before it is moved to the market. Unfortunately, the fuel also has a very low density (at 0.68 kg/m<sup>3</sup> its density is only about 0.08 percent that of crude oil), and hence for decades, its transportation was restricted to pipelines. This began to change only with the first gas liquefaction projects during the 1960s. When cooled to -161.5°C, the gas liquefies, its density rises to 422.62 kg/m<sup>3</sup>, and the liquid can then be transported in ships in well-insulated containers. The cargo is regasified and fed into a pipeline at an overseas destination.

This expensive technique was demonstrated for the first time in 1959 with the shipments of LNG from lake Charles, Louisiana, to Canvey Island in the mouth of the Thames by the *Methane Pioneer*, a World War II

Liberty-class freighter that had been converted to a small (5,000-m<sup>3</sup>) tanker. In 1964, the British Gas Council began importing LNG from Algeria, and the *Methane Princess* and the *Methane Progress* (27,400 m<sup>3</sup>) were Europe's first purpose-built LNG tankers (Corkhill 1975). In 1969, the *Jules Verne* (40,000 m<sup>3</sup>) launched French imports from Libya, and in the same year, the *Polar Alaska* and *Arctic Tokyo* (each 71,500 m<sup>3</sup>) began shipments of Alaskan LNG to Japan. In the 1970s, the United States built regasification terminals for Algerian gas in Lake Charles, Louisiana; Everett, Massachusetts; Elba Island, Georgia; and Cove Point, Maryland (the last two were mothballed in 1980).

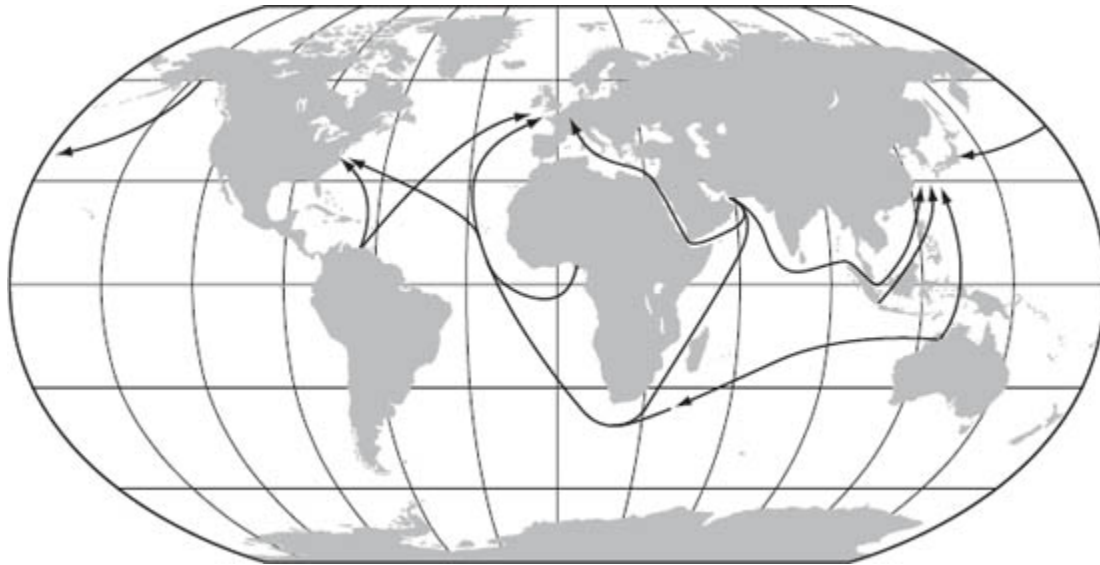
The first tankers had a membrane design, and the Kvaerner-Moss spherical containers (aluminum shells covered with insulation inside steel tanks) were introduced in 1971. The deregulation of U.S. natural-gas production (resulting in increased domestic extraction) and the retreat of energy prices after 1985 reduced interest in new (and still very expensive) LNG schemes. The first major new development in the Western hemisphere came in 1999 with the opening of a large liquefaction plant in Trinidad and Tobago. Its exports led to the reactivation of the two closed U.S. regasification plants. In contrast, there was steady progress in East Asia as Taiwan, South Korea, and China joined Japan in importing LNG from Southeast Asia, Australia, and the Persian Gulf.

Although an entire LNG system is now considerably cheaper than it was even just two decades ago, it still requires a multibillion dollar investment. The capacities of new liquefaction plants increased from about 1 Mt of LNG per year during the early 1970s to 2 Mt/year by 1990 and 3 Mt/year a decade later. The largest sizes are now up to 8 Mt/year, requiring a larger initial investment as well as a larger complement of LNG tankers (Eaton et al. 2004). A typical 5 Mt/year LNG plant requires about 110 MW of electricity to compress the gas and 60 MW for the cooling, and it costs at least \$1.5 billion. A similar sum has to be spent on six LNG tankers to transport the gas and at least half a billion on a regasification facility. Not surprisingly, minimizing the cost of LNG transport has been an important consideration, and after decades of relatively slow growth of ship sizes, economies of scale are now changing the industry as much as they had previously changed the cost of oil-tanker shipments.

After a relatively rapid initial increase in LNG tanker volume came a decades-long period of very slow growth and stagnation (partially caused

by the restrictions on tanker size in Japan, the leading LNG importer). As a result, it took almost thirty years to go from ships of 125,000 m<sup>3</sup> to vessels able to carry more than 200,000 m<sup>3</sup> s. By the beginning of 2008, there were 250 LNG tankers with the total capacity of 32 Mm<sup>3</sup> (183 Mt/year) and an average volume of 130,000 m<sup>3</sup> and in 2007, they carried 226 Gm<sup>3</sup> or 29 percent of all internationally traded natural gas (British Petroleum 2008). Fifteen countries were exporting LNG in 2008, led by Qatar (about 17 percent of the total) and followed by Malaysia, Indonesia, Algeria, Nigeria, Australia, and Trinidad and Tobago; Japan bought nearly 40 percent of all exports, followed by South Korea, Spain, the United States, Taiwan, and France (fig. 6.7; British Petroleum 2008).

But the market is set to change considerably. From an economic point of view, the global liquefied natural gas trade has begun to move away from highly standardized, highly risk-averse supply contracts to a more flexible, market-oriented mode characterized by gas-to-gas competition (Jensen 2003). A major change has taken place in standard LNG tanker design. For decades, liquefied gas was shipped in huge, heavily insulated spherical steel tanks emplaced on rings bolted to the vessel's hull. This arrangement makes for an inefficient use of the vessel's overall space, and the weight of the steel spheres increases the ship's draft, a problem for the largest tankers, which carry in excess of 150,000 m<sup>3</sup>. A new technique has eliminated both of these disadvantages. Insulated membrane tanks are made from thin stainless steel (backed by perlite-insulated plywood boxes or by foam pads) and shaped as tanks fitting the inner hull. A larger gas volume can be carried by the same-size vessels without increased draft (see fig. 5.2).



**Figure 6.7**  
Major trade routes of liquefied natural gas in 2007 (British Petroleum 2008).

As a result, sizes of the LNG tankers on order have increased appreciably. The average size of ships ordered in 2007 was about 180,000 m<sup>3</sup> and Qatargas has taken delivery of the first tankers belonging to the new two classes of Q-Flex (210,000 m<sup>3</sup>) and Q-Max (266,000 m<sup>3</sup>) ships. The company (now using eleven 135,000 m<sup>3</sup> vessels for exports to Japan) will eventually have forty-five of these large membrane-type ships powered by MAN B&W two-stroke low-speed diesels (Qatargas 2009). Another interesting innovation in LNG shipping has been the introduction of dual-fuel electric propulsion, which was first installed on tankers built by Hyundai Heavy Industries in 2005. The electricity to drive the propellers can be generated either by using the standard method of burning marine diesel fuel or by using boil-off gas from the ship's cargo.

Even with these innovations, liquefied natural gas tankers remain considerably more expensive to build than do oil tankers of much larger capacity. Recently, a 125,000 to 138,000 m<sup>3</sup> LNG tanker cost nearly twice as much (about \$200 million) than a 250,000-dwt (very-large crude carrier) oil tanker that could be had for \$120 million (Intl. Maritime Organization 2008). And because crude oil has 50 percent higher energy density than LNG (roughly 36 MJ/L 24 MJ/L) that VLCC would be actually transporting four to five time as much energy per shipment. But gas is a much cleaner

fuel with lower carbon content, which is why important developments are underway to bring new sources of LNG to the market.

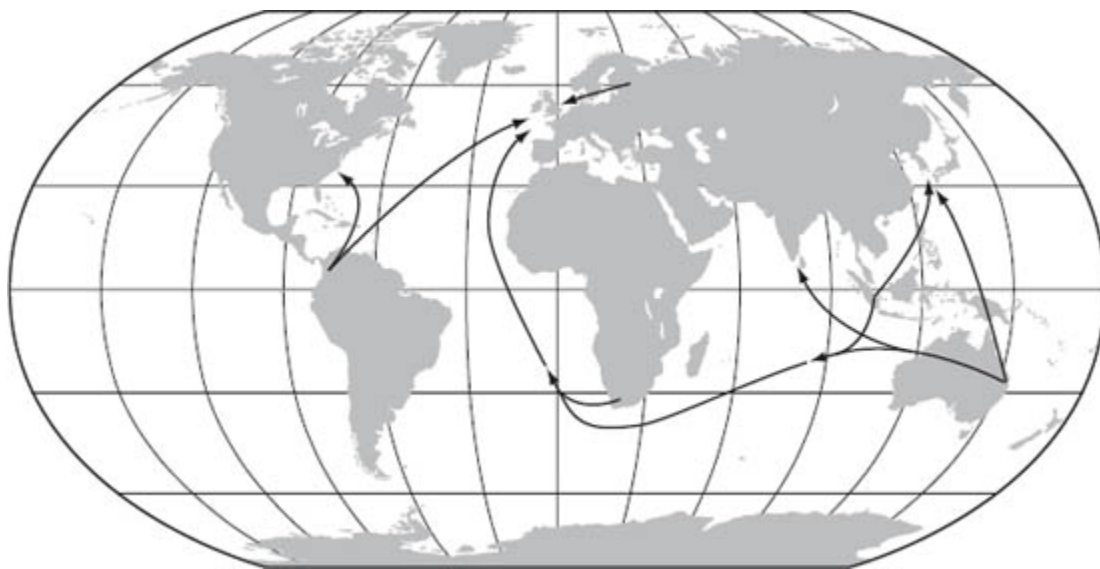
Equatorial Guinea became an LNG exporter in 2007, and new export schemes are under development in the Middle East to take more LNG to East Asian countries. Russia's LNG project on the Sakhalin Island (eventually shipping 9.6 Mt year) began its operation in 2009. Shelved plans had LNG coming from a giant Shtokman gas field (containing at least 3.7 trillion m<sup>3</sup> of gas) in the Russian sector of the Barents Sea across the Northern Atlantic to the United States by 2010. China (soon to have six regasification terminals) and India are emerging as major new importers, and Qatar is determined to become an even more dominant force in the global LNG market.

Before the global economy began to contract in 2008, the outlook was for more than 300 LNG vessels to be operating in 2010 with a total capacity of about 250 Mt/year and with a steady expansion continuing during the next decade. Whatever the eventual total, one worry has been allayed by nearly half a century of LNG trade. Concerns about safety due to massive gas-pool fires (particularly with an uncontained spill on water) and (much less likely) accidental explosions remain, but an outstanding safety record has greatly reduced their intensity. After 9/11, concerns also arose about the potential use of LNG tankers in terrorist attacks (Havens 2003).

Yet another notable recent development concerning the international energy trade is the possibility of compressed natural-gas (CNG) shipments. Unlike liquefied natural gas, where the liquid occupies just 1/600 of the gas volume, CNG volume is reduced only to 1/300 of the gaseous methane volume. When compared to LNG, there would be a smaller mass to carry per unit of ship's cargo space, but there would be less energy spent on compression, and thinner steel tank walls would make for a lighter ship. The best design by Kawasaki Kisen Kaisha is based on a pipe tank module, with a set of twenty-four steel pipes just over 1 m in diameter and 36 m in length (Kawasaki Kisen Kaisha 2008). A CNG ship (306 m long and with a full load draft of just over 10 m) would have 100 of these sets (for a total of 2,400 pipes), would carry nearly 23 Mm<sup>3</sup> (or almost 20,000 t) of methane, and would travel at 18 knots when powered either by a two-stroke diesel engine directly connected to a propeller shaft or by first powering an electric motor.

Seaborne exports of the five leading dry bulk commodities have also seen major increases. Their worldwide total rose from 900 Mts in 1980 to almost exactly 2 Gt by 2007 (UNCTAD 2008). Steam and coking coal shipments totaled about 790 Mt, iron ore 792 Mt, grain shipments about 300 Mt, bauxite and alumina 82 Mt, and phosphates just over 30 Mt. These totals mean that in 2007 about 15 percent of all extracted hard coal, 44 percent of all iron ore, 19 percent of all cereal grains, 30 percent of bauxite and alumina, and nearly 20 percent of phosphates were shipped overseas (U.S. Geological Survey 2008). A wide variety of other dry bulk cargoes added another 1 Gt in 2007. About 270 Mt of steel products and roughly 175 Mt of wood products were the two largest categories. Coke, pig and scrap iron, various mineral ores, and cement amounted to about 335 Mt, and minor dry bulk cargoes dominated by agricultural products (sugar and feed meals) and fertilizers totaled about 275 Mt.

Thanks to cheap diesel power, coal is now traded in far larger quantities than when it was the world's dominant fossil fuel. In 2007, 790 Mt (more than 85 percent of all coal exports) were shipped overseas, with nearly 75 percent of that as steam coal for electricity generation (World Coal Inst. 2009). Australia (with nearly 250 Mt), Indonesia (just over 200 Mt in 2007), Russia, Colombia, and South Africa are the leading exporters, and Japan, South Korea, Taiwan, and India the top importers (fig. 6.8).



**Figure 6.8**  
Major trade routes of coal (World Coal Institute 2008).

Perhaps nothing better illustrates the disappearance of distance as a major factor in selecting the source of bulk imports than the recent rise of coal purchases for English coal-fired electricity-generating plants. The United Kingdom's coal extraction totaled 130 Mt/year as recently as 1980, but the high cost of British deep coal mining, the low cost of foreign coal, and the very low cost of diesel-driven transport reversed the situation. By 2001, more coal was imported (35.5 Mt) than produced domestically (32 Mt), and by 2007, imports of 50 Mt were more than twice UK production (Janes 2006; World Coal Inst. 2009). The United Kingdom is now the world's fifth largest coal importer (following Japan, South Korea, Taiwan, and India), and English power plants now get most of their coal from Russia, South Africa, Colombia, Indonesia, and Australia. Not only has the old adage about bringing coals to Newcastle become a quotidian reality, but it is now coal to Newcastle from the antipodes—and at a cost lower than coal from the Midlands.

Steel remains the most important metal of modern civilization, and most of the pig iron needed to make it is still smelted from iron ore (Smil 2006). Global extraction of iron ore surpassed 1.5 Gt in 2005 and reached 1.8 Gt in 2006 (with the metal content of 945,000 t), and nearly 45 percent of it was traded, with longdistance (extraregional) shipments amounting to some 600 Mt. Australia and Brazil are by far the largest exporters (each shipping roughly 250 Mt in 2006) followed by India, Canada, and South Africa. The world's largest bulk carrier, the *Berge Stahl* (built by Hyundai shipyards in 1986 and powered by a MAN B&W 7690MCE, 20.6-MW diesel engine with a top speed of 13.5 knots) is also the world's largest iron ore transporter.

At 364,768 dwt, the ship is so large (343 m long, a 65-m beam, a 23-m draft) that it can dock in only three ports: it brings iron ore from the Terminal Marítimo de Ponta da Madeira in Brazil or from Saldanha Bay in South Africa to Europort in the Netherlands. China is the largest iron ore importer, followed by Japan, Germany, and South Korea (World Steel Assn. 2009). Steel production surpassed 1 Gt in 2004 and reached 1.34 Gt in 2007, with China producing a third of the total and Japan and the United States being distant second and third, and longdistance (extraregional) seaborne exports of steel reached nearly 250 Mt in 2006 (World Steel Assn. 2009). The international scrap trade reached almost 90 Mt by 2006, with the United States the leading exporter.

Trade in agricultural products has been steadily increasing since the 1950s. Its most massive component is the export of cereals, led by the sales of corn and wheat (rice trade is limited) and by exports of soybeans. Global harvests of wheat, corn, and soybeans now add up to nearly 1.6 Gt, of which about 300 Mt were sold overseas in 2007 (UNCTAD 2008). Coarse grains (feed corn, barley, oats, rye, and soybeans) dominated the trade with about 200 Mt, and wheat shipments added just over 100 Mt. The United States has been the most important exporter of wheat for several generations, followed by Canada and Australia. The country is also by far the largest exporter of feed corn and, with Brazil and Argentina, one of the three dominant exporters of soybeans. Asia has been the main recipient of grain imports (led by Japan) followed by Latin America and the Middle East.

But this comparison underestimates the role of shipborne agriculture trade because the traded mass is not the best indicator of its importance. On the one hand, shipping cereals to chronically grain-deficit nations (including such populous countries as Egypt or Iran) or to countries or regions experiencing temporary food shortfall or famines is literally a life-saving endeavor (repeated international aid to Ethiopia and Somalia is perhaps the best example). On the other hand, trade in specialty food and beverage commodities (in fruits, vegetables, nuts, spices, cocoa, coffee, and tea) is not important because of its aggregate mass but because of its relatively high value. For some of the exporting nations, such trade is the leading earner of foreign exchange. Exports of these specialty crops has been taking place increasingly in containers rather than in bulk carriers, a shift that reflects both higher rates for bulk carriers and the economies of massively containerized transport.

### **Intercontinental Shipping: Container Vessels**

Traditional break-bulk shipping—costly, inconvenient, and time-consuming—was one practice that did not change when steam-powered ships replaced sailing ships. Although Thoburn C. Brown used aluminum boxes for shipping in the 1930s and introduced sturdier small (2.4-meter long) containers to move goods for the U.S. Army in World War II, containerization on an industrial scale did not take off until the late 1950s. Its unlikely pioneer was Malcolm Purcell McLean (1914–2001), and the



genesis of this truly revolutionary innovation—the gradual diffusion of a new transport method, its mature development, its organizational changes, and its economic consequences—have been described and assessed in considerable detail by Pearson and Fossey (1983), Chadwin, Pope, and Talley (1990), Kendall and Buckley (2001), Broeze (2002), Cudahy (2006), Levinson (2006), and Donovan and Bonney (2006). Here I present only the basic outline of the history of container shipping and its major milestones.

Malcolm McLean, the industry's great pioneer, was neither a shipping executive nor a maritime engineer but a North Carolina trucker who, as he later frequently retold the story, had his eureka moment in 1937, when he had to wait most of the day to have his bales of cotton unloaded at the Hoboken docks in New Jersey (fig. 6.9). Would not it be easier to have his trailer lifted up and put on the ship without its contents being touched? But there was no immediate follow-up on that great idea, and it was not until 1955 that McLean began to put his plan in place. He acquired the Pan-Atlantic Steamship Company, an operator of small tankers between the U.S. northeast and the Gulf of Mexico, and soon afterward its parent company, Waterman Steamship Company (Kendall and Buckley 2001; Cudahy 2006).



**Figure 6.9**

Malcolm McLean, the pioneer of containerization, inspecting one of his far-flung operations. Photograph courtesy by Maersk Group.

Rather than commissioning a new specialized and hence necessarily expensive container-carrying vessel, he chose to convert a readily available ship, and he followed this procedure for the next fifteen years before he finally ordered a new ship design. The first conversion entailed the erection of a steel skeleton deck above the main deck of a World War II-era T-2 tanker renamed by McLean the *Ideal X*. The deck had sockets to accept the stubby feet of a new truck trailer that was reinforced vertically for stacking and horizontally for lifting and crane loading. On its first trip on April 26, 1956, the ship carried fifty-eight large (35-foot, 10.5-m) containers (weighing in total about 1,000 tons) from Newark, New Jersey, to Houston, Texas. The first successful trip led to the launching of the *Gateway City* on October 4, 1957. The ship was a converted C-2 freighter fitted with cellular compartments and able to transport of up to 226 large containers stacked within a steel framework erected in the hold.

This was the world's first fully cellular container ship in which containers were fastened by twistlocks into huge blocks: four layers were stacked in the hold, and two on the deck. Five other C-2 ships were converted in 1957, and all were equipped with the special cranes for loading and unloading that were needed before the ports acquired new spreader machines that could lift the containers by inserting hooks into corner holes. The new industry's second beginning took place on America's West Coast when Matson Navigation Company decided in 1956 to convert its California to Hawaii service (began in 1882) to containers. The *Hawaiian Merchant*, a converted C-3 freighter, shipped twenty containers on its deck from Los Angeles to Honolulu in August 1958, and in April 1960, the *Hawaiian Citizen* became the company's first all-container vessel, with a capacity of 436 7.2-m-long units (Matson Co. 2009).

In 1958, McLean added Puerto Rico to his container-ship destinations, and in 1960, he renamed his company Sea-Land and began to expand its operations beyond the East Coast to the Gulf of Mexico and Puerto Rico service. In 1961, the first of the company's new four converted T-3 tankers, the *Elizabethport*, was the first container ship to sail through the Panama Canal to the West Coast. In 1962, Sea-Land ships began operating from the Port Elizabeth Marine Terminal in Newark, New Jersey, and Alaska service was added in 1964. In April 1966, the company began a regular service to Europe with the SS *Fairland* carrying 226 containers to Rotterdam. Conversions of freighters to container ships continued throughout the late

1960s, when containerization received a major boost because of the Vietnam War. By 1968, the U.S. Department of Defense had used more than 100,000 containers to speed up the delivery of military supplies.

In that year, McLean also launched the first fully containerized service to Japan. A year later, when he sold Sea-Land to R. J. Reynolds (but stayed on as its president), the company had 27,000 containers. Finally, in 1972, Sea-Land received its first new designs—eight SL-7-class ships, 284-m-long, 27,358-dwt vessels that were capable of very fast speeds of 33 knots and were powered by General Electric 45-MW steam turbines. Their speed was bought by a very high consumption of bunker fuel, whose price more than tripled by 1974. As a result, all subsequently launched container ships by Sea-Land (or by any other maritime freight company) were diesels. During the 1970s, container shipping entered its mature organizational stage. Fleet and ship capacities continued to increase, but schedules and routes were optimized, and by 1980 there were for the first time more fully cellular ships than semicontainerized vessels (Pearson and Fossey 1983).

In 1986, Sea-Land was sold to CSX, and in 1999 it was bought by the Danish Maersk to form Maersk Sealand, the world's largest container shipper (Maersk Line 2009b). By the late 1980s about 90 percent of the total value of international seaborne trade moved in containers. Leaving aside raw materials and commodities that must be moved in bulk (materials that can be pumped on board, such as crude oil, refined products, and liquid chemicals, or that can be dumped into large holds, such as metallic ores, coal, and grains), containerization of the global trade was virtually complete. Moreover, some commodities that were previously shipped only by bulk carriers (including bundled paper and plastics for recycling and some metallic ores and agricultural products) are now shipped in containers. As a result, the share of containerized cargo rose from less than 5 percent of all seaborne shipments in the early 1980s to nearly 25 percent by 2008. The only important exception of a high-value cargo that cannot be transported either by bulk carriers or container vessels is cars.

Individual vehicles are often (legally and illegally) moved in sealed containers, but mass commercial exports, amounting annually to millions of units, are done by specialized roll-on roll-off (ro-ro) ships. This type of ship was first used as a much more convenient ferry (replacing the slow laborious loading of cars by cranes), and their capacity grew with the intensification of intercontinental car exports in the 1960s (in the U.S., the

Volkswagen Beetle sold more than 100,000 units for the first time in 1960, and its sales peaked at 423,000 units in 1968) and the 1970s (with the sales of such now iconic machines as the Honda Civic, Honda Accord, and Toyota Camry).

Before citing the key statistics charting the progress of containerization, a short definitional detour is necessary to explain the genesis and meaning of the standard unit that has been used to gauge the performance of containerized shipping. Everybody is now familiar with containers—even those people who have never seen a cargo port or a container ship can see them on highways as they are trucked to their final destinations—but few people take a closer look (fig. 6.10). If they would, they could see that every container is readily identifiable by a unique combination of four letters (assigned by the Bureau des Containers for the operator) and by seven digits that make it possible to use constant computerized tracking. Geometrically speaking, shipping containers are rectangular prisms made of steel with reinforced edges and corners. Because of the industry's American origins, their primary dimensions are given in feet rather than in meters.

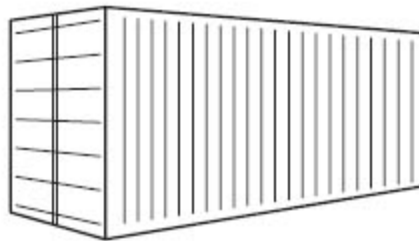
To be transportable by trucks, their width is fixed at 8 feet (2.4 m), and their height varies only a little, between 8.5 and 9.5 feet, but their lengths range from just 10 feet (3-m pupainers that are more commonly seen in Europe) to as much as 53 feet (nearly 16 m), but 20-foot and 40-foot containers are the most common sizes in use. Their empty weight is, respectively, 2.2 and 3.7 t, and they can carry a maximum load of 21.7 and 26.8 t and have volumes of roughly 33.2 and 67.7 m<sup>3</sup> (fig. 6.10). Identically sized reefers (refrigerated containers) have less internal space (28.3 and 57.8 m<sup>3</sup>) because the refrigeration unit cannot extent beyond the standard outsize dimensions.

McLean began with 35-foot-long containers, but two sizes—20-foot and 40-foot-long units—soon came to dominate the industry, and it was the first one that a British journalist Richard F. Gibney (working at Shipbuilding & Shipping Record) chose in 1969 as the common denominator for statistical comparisons. Every aspect of the industry—its total global and national capacity, its annual shipments, the capabilities and rankings of the largest container ports, the capacities of individual container ships or the largest container operators—has been measured and compared in the twenty-foot equivalent unit (TEU) (alternatively, the trailer equivalent unit), although

the 40-foot units (equal to 2 TEUs) have accounted for most of the containers in service since the mid-1990s.

As already noted, in 1956, McLean's *Ideal X* could carry just 100 TEUs. In 1957, his first fully cellular ship could carry 400 TEUs, a decade later the maxima reached 1,300 TEUs, and McLean's first new vessels (SL-7) in 1972 and 1973 accommodated 1,968 TEUs. In the 1970s came the first diesel-powered ships of 3,000 TEUs, and by the early 1980s, the typical capacities of new vessels approached 4,000 TEUs. The first ship able to carry 6,000 TEUs was the *Regina Maersk*, which was launched in 1996. By the decade's end, Maersk Sealand had S-class ships that carried 6,600 TEUs. In 1999, the *Sven Maersk* reached a capacity of 7,500 TEUs, and by 2003, maximum capacities surpassed 8,000 TEUs.

Since that time, several new records have been set by South Korea's Samsung Heavy Industries, the company that has nearly half of the global market share for new large container vessels. In 2005, it set a new record with a 9,200-TEU ship and surpassed it in less than a year by launching the 9,600-TEU *Xin Los Angeles*, the first of eight identically sized vessels powered by MAN's 68.52-MW engines and owned by the China Shipping Container Lines. These vessels, crewed by nineteen men, are 336.7 m long and can carry eighteen rows of containers by eight tiers on the top deck and sixteen rows by ten tiers in the hold. But by 2006, the company's chief executive officer disclosed that Samsung already has a design for a 12,000-TEU ship and was working on a 14,000-TEU ship.



**standard 20 foot**

inside height 2.38 m  
inside length 5.89 m  
inside width 2.33 m  
maximum cargo weight 21,727 kg

**standard 40 foot**

inside height 2.38 m  
inside length 12.01 m  
inside width 2.33 m  
maximum cargo weight 26,780 kg

**Figure 6.10**  
Offloading containers from a Maersk ship and the inner dimensions of the two most common units.  
Photograph available at the Maersk Web site.



**Figure 6.11**

A stern view of the *Emma Maersk*, the world's largest container ship. Photograph available at the Maersk Web site.

The largest container ship in 2008 was the *Emma Maersk*, built for the Maersk Line at Odense Shipyard (it cost \$145 million) and put into operation in September 2006 (Maersk Line 2009a; [fig. 6.11](#)). The 397-m long ship (more than 50 m longer than either the USS *Enterprise* or the *Berge Stahl*, the world's largest bulk carrier) rates the equivalent of nearly 157,000 dwt, and although the company puts its nominal capacity at 11,000 TEUs, the International Maritime Organization rates it at 13,800 TEUs, including 1,000 refrigerated units. Just three more superlatives indicating the vessel's size: its anchor weighs 29 t, it travels more than 300,000 km in a year, and if all the containers it carries were moved on rails, the train would be 71 kms long. As already explained, its prime mover is Wärtsilä's 80 MW 14Rtflex96c engine, and it also has five Caterpillar diesels as electricity generators. By recycling exhaust (mixing it with air and feeding it back to the engine), it achieves a 12 percent boost in overall efficiency.

But all major maritime companies operate some very large double-hulled and double-bottomed ships (this now means with capacities above 6,000 TEUs) with multiple layers of containers stacked below the deck line (the ships have actually no closed deck) and two or three layers fewer above it. And because of their similarly sized prime movers (MAN B&W or Wärtsilä

diesel engines), all of the ships of a similar size travel at nearly identical speeds. As for the total numbers, the worldwide fleet of fully cellular ships grew from six vessels in 1957 to 845 ships by 1980. A decade later, there were nearly 1,250 vessels, by the century's end just over 2,600, and the total jumped from about 3,350 in 2005 to almost 4,300 at the beginning of 2008, when, after a period of record orders, some 5,200 ships were expected to be in service by 2010, a total that appeared increasingly unlikely as economic prospects worsened during that year.

The total carrying capacity of these ships was about 10.8 million TEUs in early 2008 compared to 4.5 million TEUs in 2000 and 1.7 million TEUs in 1990. Average ship capacity rose from about 1,400 TEUs in 1990 to about 2,500 TEUs in 2008 when the modal size of new ships on order was about 3,400 TEUs and the largest ships under construction exceeded 10,000 TEUs. A few giant companies have come to dominate the field. The Danish Maersk Line (the key component of the Maersk-A. P. Møller group, whose first container vessel, the *Svedenborg Maersk*, was put into service in 1974) is the unrivaled leader, with more than 1.6 million TEUs in 2008. The Swiss-based MSC had 1.2 million TEUs, the French CMA-CGM Group 700,000 TEUs, Taiwan's Evergreen Line 620,000 TEUs, and the German Hapag-Lloyd nearly 500,000 TEUs. These make up the leading five, whose capacity added up to 37 percent of the early 2008 global total of 12.657 million TEUs (UNCTAD 2008). The next five largest shippers (China's COSCON and CSCL, Singapore's APL, Hong Kong's OOCL, and Japan's NYK) bring the capacity of the top ten to just over 50 percent of the total.

The ships sail according to demanding schedules either by constantly shuttling between two ports or making often extended circuits with stops at the major container terminals of several continents. The ranking of ports by their container-handling activity involves frequently more than two port moves (that is, loading at the source and unloading at the destination). According to the U.N. Commission for Trade and Development (2008), the share of trans-shipments in container-port throughput increased from just 10 percent in 1980 to 27 percent by 2007, a trend that raises the global container-port throughput to more than three times the actual volume of trade. For many years, Hong Kong used to be the world's busiest container port, to a large extent because it is a prime example of a port with a very high rate of trans-shipments as a variety of smaller feeder vessels (Hong Kong harbor is full of them) bring in the boxes to be loaded on large



transoceanic ships. In addition, many empty containers have to be repositioned repeatedly.

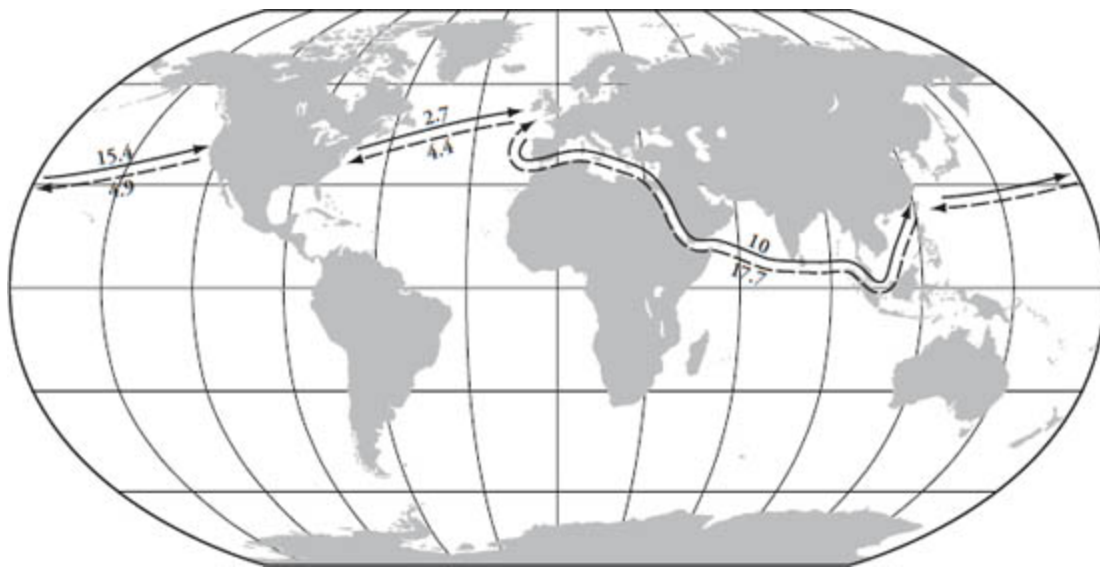
In 2005, Singapore (another port with a high share of trans-shipments from countries of the Southeast Asia) beat Hong Kong by about 600,000 units by handling 23.2 million TEUs, with Shanghai, Shenzhen, and South Korea's Busan making up the top five. By 2007, Shanghai (26.1 million TEUs) was second to Singapore (27.9 million TEUs), with Hong Kong, Shenzhen, and Busan among the top five. Rotterdam (with 10.8 million TEUs), Hamburg (9.9 million TEUs), and Los Angeles (8.3 million TEUs) were the busiest receiver ports in 2007 (UNCTAD 2008). As is the case with the shipping companies, there is a highly skewed distribution of port activity, with the top 20 percent ports accounting for 48 percent of all traffic in 2007.

Worldwide container-port traffic amounted to about 200 million TEUs in 2000, more than twice the 1990 total, and by 2006, it reached 434 million TEUs. There are three major sea lanes of containerized trade, all along the east-west axis. After overtaking the trans-Pacific lane in 2007, the Asia-Europe stream is now the largest one, with nearly 18 million TEUs moving westward and 10 million shipped eastward, with most of this traffic going through the Straits of Malacca, Bāb al-Mandāb, the Suez Canal, and the Mediterranean. There is an even greater imbalance of traffic on the second key route between North America and Asia, with three times as many loaded containers leaving Asia. And in 2007, the trade between North America and Europe involved about 4.4 million TEUs moving westward and 2.7 million TEUs traveling eastward ([fig. 6.12](#)).

China's post-1990 emergence as a new manufacturing hub of the world would not have been possible without inexpensive diesel-powered containerization. Although China continues to export various raw materials and bulky industrial commodities (coal, rolled steel, and cement), an overwhelming share of its recent exports (about 95 percent by value) has come from a wide range of manufactures, with mechanical and electrical products accounting for nearly 60 percent of total value and what Chinese statistics call "high-tech and new products" for almost 30 percent. All of these products leave China in containers, and as a result China has emerged as the world's leading country of origin for containerized seaborne traffic. In 2006, China's container traffic (including Hong Kong) reached about 108

million TEUs or nearly 25 percent of the world total of 434 million TEUs (UNCTAD 2008).

China now has four ports (Shanghai, Hong Kong, Shenzhen, and Qingdao) among the world's top ten, three ports (Ningbo, Guangzhou, and Tianjin) among the next ten, and a 45 percent share of the throughput in the world's top twenty container terminals. This transformation has been even more impressive considering the fact that in 1980 the country had no modern container port. Thanks to containers, it has become largely irrelevant if Chinese-manufactured exports are made of locally produced cheap raw materials (wearing apparel or plush stuffed toys) or if they are assembled from expensive components that are imported from other countries (electronic devices ranging from cell phones to laptops). Nor does it matter if they are destined for exports to North America, Europe, or Africa.



**Figure 6.12**

Major interregional shipments of containers. Numbers are twenty-foot equivalent units that were moved in 2007 (plotted from data in UNCTAD 2008).

China's low-cost, disciplined, flexible, and nonunionized labor has been the primary factor for setting up the manufacturing plants, and the low costs of intercontinental shipping did not make it even a secondary consideration in making this decision, a perfect example of eliminating distance to market as a decisive factor in industrial location thanks to inexpensive diesel fuel. How low those shipping costs are can be seen by comparing their shares (in 2007

and the first half 2008) with the retail price of common consumer products. For a TV set retailing for \$500 to \$700, the shipping costs of \$10 are as low as 1.5 percent of the price, for a DVD player selling at \$200 they are only 0.75 percent, and for small items (mobile phones, small bags of coffee beans, chocolates, or beer), they amount to around 1 percent of the retail price (Intl. Maritime Organization 2008). All of these shares fell significantly by the end of 2008 as a result of the sharp reduction of global oil prices and, even more important, the unprecedented drop in charter rates brought about by the global economic recession.

There is an important additional reason why the term *revolution* is not hyperbolic when describing the reality of the post-1950 impact that large diesel engines have had on ocean shipping. These shipments are not only voluminous and inexpensive but also very fast and highly reliable. At the beginning of the twentieth century, small (typically 5,000 to 6,000 dwt) general-purpose cargo ships traveled at about 15 km/h, powered by bulky and inefficient coal-fired steam engines and loaded and emptied by time-consuming and only partially mechanized labor. In contrast, the largest container ships must adhere to taxing schedules as their powerful diesels propel them at speeds of up to 46 km/h and with an efficiency unsurpassed by any other mobile prime mover.

Moreover, modern cargo ships can be loaded and offloaded about twenty times faster than their counterparts in 1950—by cranes that are themselves often powered by diesel engines. During the earliest period of containerization, gantry cranes could handle just twenty containers per hour. By the 1980s, they could move thirty containers every hour, and a 3,000-TEU ship could be thus offloaded with two cranes in two days (Gubbins 1986). Now the largest Liebherr gantry crane spreaders can make twinlifts of up to 65 t and tandem lifts of up to 80 t (two 40-t containers) at one time, and some of them can reach up to 65 m from the dockside—that is, across 25 TEUs (Liebherr 2009b). To turn around a 6,000-TEU ship in less than twenty-four hours, crane operators make seventy-five to a hundred moves per hour, and the rate must go up to two hundred moves per hour for an 8,000-TEU vessel. The highest discharge rates (300 TEUs per hour) are now in ports with indented berths (such as Amsterdam's Ceres Paragon terminal), where ships are accessible from both sides (Valentine 2008).

Straddle carriers and reach stackers (used to deposit and remove containers prior to further land shipment) are also commonly powered by

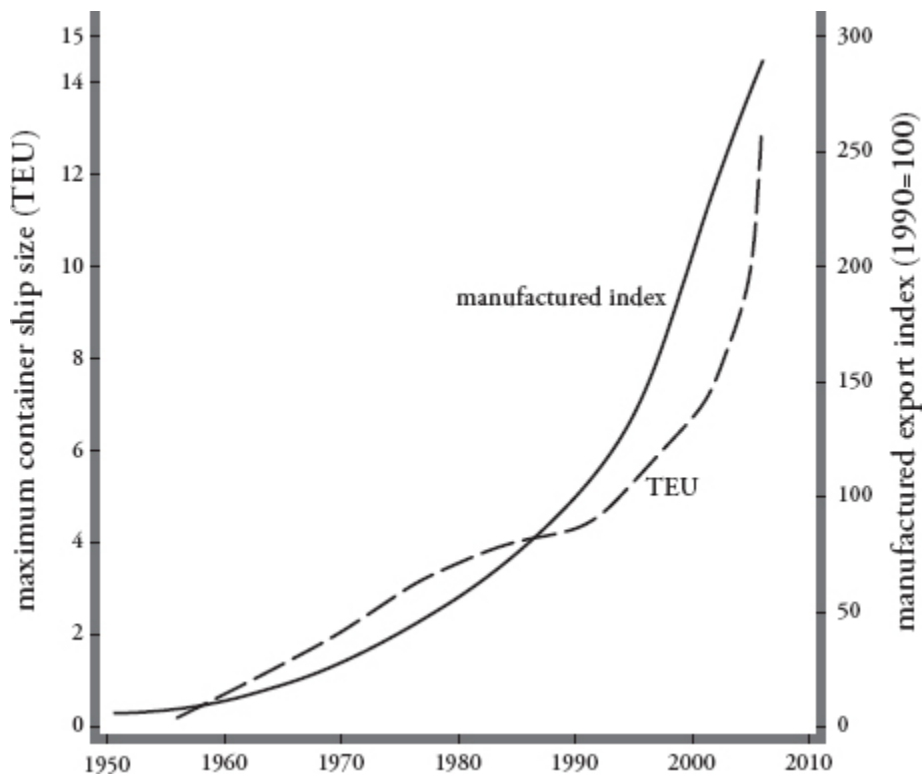
diesel engines, as are large trucks and long container-carrying trains that take the containers to their final inland destinations. The development of this intermodal system has been an essential part of global containerization. Large deliveries by large container ships would create massive portside bottlenecks without well-organized transfers to trucks, railroad cars, or barges. Loading standard containers on heavy trucks could be done with only small modifications, but railways needed to reorganize as they shifted from traditional break bulk shipments to containerized cargos. But their adjustment began years before the appearance of first container ships. They began to convert during the 1950s to intermodal trailer-on-flat-car (TOFC) piggyback shipments of truck trailers—the rectangular boxes with permanently attached wheels.

Not long after the TOFC became a common mode of railway transport, railways had to switch to a new container-on-flat-car (COFC) mode. Once it got underway, the switch proceeded rapidly. In 1985, nearly 80 percent of all U.S. intermodal moves involved trailers, and by the year 2000, 75 percent of all carried units were containers (Intl. Air Transport Assn. 2009). As already noted, APL introduced Stacktrain in the mid-1980s, and that innovation required the lowering of car beds to just 30 cm above the rails—to fit the two containers within the standard height limits, the reduction of longitudinal and lateral movements through special connections, and the restriction of vertical motion by placing wheel assemblies closer than in standard cars (as closely as 15 m, compared to the standard of 24 m). Double-stack now dominates containerized freight transport on railroads (see fig. 5.21).

Positive effects and undeniably advantages are not in short supply when reviewing the first five decades of containerization. No other system has contributed as much to the globalization of trade and to the rise of the global supply chain of economic interdependence as the adoption of intermodal container transportation, which links producers with other producers and producers with consumers via sturdy steel boxes carried by trucks, railroad cars, ocean-going vessels, and barges. Everybody is now well aware of the second (producers-to-consumers) link as millions of boxes carry Asian manufactures to retailers around the world.

But the first link has had no less profound effects on modern economies as producers have been able to reduce their inventories and to lower their operating costs by relying on the dependable, incessant deliveries of parts

and components that are needed to assemble or to finish their products. Ratios of inventory to GDP have thus decreased in the United States (by perhaps as much as \$2 trillion between 1980 and 2008) as well as in China, where the assembly of many consumer products (particularly of electronic devices) depends on just-in-time deliveries of components ranging from plastic moldings to microchips. An impressive demonstration of the cause-and-effect relationship between diesel engines and global trade can be made by plotting the maximum sizes of container ships and the growth of manufactured exports that now travel almost exclusively (except for cars carried by roll-on roll-off ships) in steel boxes (fig. 6.13). More powerful, more efficient, and more reliable diesel engines have made it possible to increase the size of container ships from 210 TEUs in 1956 to 11,000 in 2006, roughly a fiftyfold gain. During the same time, global merchandise exports increased nearly thirteenfold.



**Figure 6.13**

The growth curves of global merchandise exports and of maximum sizes of container ships (plotted from data in WTO 2008, Cudahy 2006, and UNCTAD's annual *Review of Maritime Transport*).

There are many other benefits of containerization. As with all modern techniques, increased unit size has brought desired economies of scale and

lower operating costs per unit. According to the Germanischer Lloyd, the total cost (including interest payments, depreciation, fuel, crewing, and maintenance) of shipping a TEU on a 10,000-TEU vessel is 14 percent cheaper than on a 5,000-TEU ship, and going from 10,000 TEU to a Malacca-maximum 15,000 TEU should save another 11 percent per TEU. Sealed cargoes are protected against both casual pilfering and shipping damage, and hence they qualify for lower insurance rates. The combination of completely mechanized handling in ports (where the turnover rates have come close to the physical minima, determined by the size of cranes, the available dock storage space, and the supply of platforms, whether trucks or railroad cars, to move the cargo away from the dockside) and the subsequent intermodal forwarding has cut the overall delivery time of many cargoes from producers to retailers by more than 95 percent compared to the traditional ways of break-bulk handling and manual reloading.

On the other hand, some of the early advantages of ubiquitous containerization were transformed into concerns. Cargo pilfering, common with break-bulk loads in ports around the world, was undoubtedly reduced with the introduction of sealed containers, but it did not take long for criminals to devise ways to empty the contents without leaving any obvious marks of opening the box. Better yet, the hijacking of loaded containers during the truck legs of their journey became highly lucrative as some boxes loaded with high-value merchandise may carry goods worth \$200,000 to \$500,000. Organized crime has also found containers to be an excellent means of shipping concealed drugs and other contraband or to smuggle (at enormous risk to those willing to submit to such an ordeal) illegal immigrants.

But the greatest concerns arose in the aftermath of 9/11 as the new security awareness could hardly find a more worrisome way of smuggling components for weapons of mass destructions, radioactive materials, or pathogens. Given the fact that U.S. terminals have been recently receiving more than 40,000 new containers every day and that they have to process more than 15 million units a year, it is impossible to examine every box while maintaining such a throughput. One of the best ways to deal with the threat is to make many inspections in major ports of origin, a course of action adopted by the U.S. Customs Container Security Initiative.

An even more fundamental consideration is an unsustainable pace of container traffic and the consequences of future volume fluctuations or

declines. Between 1990 and 2008 (that is, during a span shorter than a single generation), container shipping was a perfect case of an industry growing at dizzying rates. Maximum ship sizes (measured in twenty-foot equivalent units) nearly tripled, the number of fully cellular vessels nearly quadrupled, and the global volume of container trade had quintupled when measured in TEUs and grew more than sixfold (to nearly 1.4 Gt) when measured in total mass (UNCTAD 2008). Such growth rates cannot be replicated in the coming generation, or by the late 2020s we would have ships of 35,000 TEUs, and container ports would have to handle more than 8 Gt of loaded containers—more than the total mass of all maritime shipping in 2008.

The construction of such giant ships would present challenges akin to building tankers larger than 500,000 dwt (possible but almost certainly not worth it), their profitability would be much more easily dented by rising fuel prices, and larger ship sizes have already made the port handling of containers a key bottleneck of the entire global intermodal system. Because of their size (requiring exceptional offloading capacities) and their draft, the largest container vessels can call on a limited number of cargo terminals where the containers (in a manner similar to the traditional hub-and-spoke operations of major airlines) must be transferred to smaller ships that are able to reach smaller ports (in 2007, about 27 percent of all container port traffic consisted of such trans-shipments). In addition, the high cost of such ships (in 2007, it was \$160 million for an 8,000-TEU vessel, compared to less than \$100 million for a similar-size bulk carrier) will become more of a concern in fluctuating or depressed markets when the vessels have to be laid up.

### **Flight on a Planetary Scale**

The higher-power, more efficient, and more reliable performance of gas turbines has been impressively reflected in the rapid evolution and diversification of jet-powered airplanes, in the unprecedented speed of their adoption, and in the exponential growth of the world's aviation industry and international air traffic (Loftin 1985; Heppenheimer 1995; U.S. Centennial of Flight Commn. 2003). After initial setbacks (due to the Comet's crashes) and hesitations about committing to a new technique were overcome, jetliners were adopted faster than any other new complex and expensive

machine in history. Their share in scheduled commercial service rose from zero in 1950 to less than 7 percent of all aircraft heavier than 9 t by 1960. But by 1962 it doubled, by 1966 it doubled again, by 1970 jets reached the 50 percent mark, by 1980 they made up about 72 percent of all planes, by 1990 the share was nearly 80 percent, and in 2005 they reached 82 percent of the total (Intl. Civil Aviation Organization 2006). This rise to dominance has been accompanied by an impressive increase in absolute numbers—from no jetliners in service in 1955 to nearly 14,000 planes in 1995 and more than 18,000 aircraft in 2005.

Three of the six designs that made up the first generation of jet aircraft launched before 1960—the Comet, the Convair, and the Caravelle—did not give a rise to long-lived families of airplanes. Tupolev’s impact remained limited while the DC-8 led to larger and better planes in the 1970s (DC-9) and 1980s (an early widebody DC-10), but McDonnell Douglas (the maker of such aviation icons as the DC-3 and the F-15 Eagle) could not survive, and in 1997 it merged with Boeing. The only unbroken design chain from the first generation of turbojet-powered airplanes to the latest models propelled by high-bypass turbofans is the one that began with the Boeing 707 and 720, continued with the most successful designs of the second generation (the Boeing 737-100 and -200), led to the first wide-body plane (the Boeing 747-100) and to the company’s current family of jetliners ranging from the latest version of the 737 (the 700-900), the wide-body 757 and 767, the long-distance 777, and the highly innovative 787. No other airplane has advanced the process of globalization as much as the Boeing 747. Its introduction marked an epochal shift in air travel (Boeing 2009c; [fig. 6.14](#)).

Remarkably, the plane was not an inevitable product of gradual technical improvements but was designed at the urging of Juan Trippe, the founder and president of Pan Am. William Allen, Boeing’s chairman, staked the company’s future on the plane’s success as he had to invest more than twice its worth in the project. The plane’s two most characteristic features—its wide body and the bubble cockpit—were dictated by the original intent to use it as a large cargo carrier. A wide body made it possible to load two standard containers side-by-side, and the bubble cockpit made it easier to load the plane through its upturned nose. Many 747s were eventually ordered in cargo versions (by 2000, they provided half of the world’s international air freight capacity), but the passenger version did not end up



as a tolerable but unexciting compromise but as the paragon of a plane that obeys ruthless engineering logic (Tennekes 1997).

Thanks to an extraordinary design and manufacturing effort, the prototype plane took off on February 9, 1969, less than three years after Pan Am ordered twenty-five planes. The first scheduled flight on January 21, 1970, had to return to the gate after an engine overheated during taxiing, but more than five hours later a back-up plane finally took off for London. The enormous plane became almost immediately an icon of technical accomplishment and a favorite of the jet age. A redesigned version, the 747-400, arrived in 1988 with digital avionics and programmable displays in the two-crew cockpit, with new high-bypass turbofan engines (the PW4000), and with an ability to fly as many as 524 passengers on nonstop flights at the edge of the stratosphere (at a ceiling of 12.5 km) from Vancouver to Hong Kong or from Singapore to London.



**Figure 6.14**

The observation deck at Tokyo's Narita Airport is one of the best sites to see 747s. This oblique view shows a Delta 747-400.

Photo by V. Smil.

On its takeoff for an intercontinental flight that can last more than twelve hours, a fully loaded 747-400 weighs close to 400 t, an equivalent of more

than six stubby-looking short-range 737-500s. About 40 percent of its mass is jet fuel, and its four engines, mounted on wings spanning more than 64 meters, deliver a peak combined thrust equal to about 280 MW of power. The one thousandth 747 was delivered on October 12, 1993, and by the end of the year 2000, the count approached thirteen hundred. Different versions of the 747 had carried some 2 billion passengers, a total equal to one third of humanity. That year, when I was asked by *Nature* to write several millennial essays, it seemed clear that one of them had to deal with the Boeing 747. This is how it ended (Smil 2000, 239):

Her size, range, speed and economy have made intercontinental flight routine, with steadily declining real costs, as tens of millions of people go to family reunions, business meetings or beaches, and billions of dollars of electronic goods, flowers, clothes and toys move to rapidly changing markets. The growing integration of the global economy in general, and Asia's economic rise in particular, have been closely tied to the international fleet of 747s. The Boeing 747 combines symbolism and function, beauty and economy: a daring, revolutionary design that has become a powerful symbol of global civilization, an improbably graceful behemoth that ushered in the age of mass intercontinental travel, its allure has not faded after three decades of unprecedented service.

Next time you are at a large international airport, find a gate with a 747. Then stand, childlike, with your face against the glass right in front of the plane's huge rounded nose, note the four massive four-wheel bogies, look up at the bubble topping the fuselage, check the enormous engines mounted on a gently arched, variably cambered wing, and sweep to its end where an upturned winglet makes it easy to identify the most modern 747-400 series. Like a Gothic cathedral or a high-flying flock of Canada geese, the 747 is an object of undeniable beauty, graceful daring and irresistible awe. How can that thing fly? How that thing can fly!

More efficient and more profitable designs followed, and with the launch of the A380 in 2007, the plane lost its rank as the largest passenger airliner. But many flight experts still believe that the jumbo was the most revolutionary, if not the best, jetliner ever built—one that changed intercontinental flight from a privileged exclusivity to an affordable experience enjoyed by billions. In any case, Boeing remains the only survivor of the great trio of post-World War II American airplane makers. In 1997, it bought McDonnell Douglas while Lockheed, the maker of an early wide-body L-1011, left the commercial business in 1984 to concentrate on military designs.

Boeing's lineup has continued with strong sales of the company's smallest plane, the Boeing 737, the bestselling jetliner of the twentieth century, with more than 3,800 planes of different versions shipped between 1967 and 2008 (Boeing 2009b; Aerospaceweb 2009a) and with three new large planes, the Boeing 757 and 767 (both introduced in 1982, the second rapidly becoming the premier trans-Atlantic plane) and the Boeing 777, first

flown in 1995. The latest entry, the Boeing 787 (Dreamliner), was intended from the outset to have a path-breaking design that uses a high share of composites and introduced a new cabin design, but problems with new materials have delayed its commercial introduction (Boeing 2009e; Aerospaceweb 2009b).

In the 1990s, Boeing lost its dominant position in the global jetliner market as it went through massive cyclical layoffs, strikes, productivity problems, and plummeting stock prices, while Airbus was increasing its share of new orders. This European consortium was set up in December 1970 with French and German participation, and it was later joined by Spanish and British companies. Its first product was a twinjet Airbus A300 (for 226 people), launched in October 1972, and the company then added a large family of jetliners ranging from short-haul planes (the A319, 320, and 321) to the long-distance wide-body A340 in 2001. In 2000, Airbus surpassed for the first time the number of planes sold by Boeing and announced its intent to build a double-decker superjumbo A380, the company's only path-breaking design (fig. 6.15).



**Figure 6.15**

An Airbus A380 at San Francisco Airport.  
Photo courtesy of Steve Kurtz, Leesburg, FL.

Its maximum takeoff weight is 560 t, about 40 percent heavier than that of the Boeing 747-400, and although it is not the longest plane (the A340 is 2.3 m longer), it is by far the highest (24.1 m versus 17.3 m for the A340) and has the longest wing span (79.8 m). The A380 cruises at Mach 0.85 (1,041 km), has a ceiling of 13,115 m, has a maximum range of 15,200 km, and needs only 2,750 m to take off (Airbus 2009). The plane could carry as many as 853 passengers in a single class, but so far the airlines have ordered only three-class configurations for 525 people (compared to 416 in three-class and 524 in two-class configuration for the Boeing 747-400). After many delays and huge cost overruns, the plane entered commercial service on October 25, 2007, with Singapore Airlines flights from the Changi airport to Sydney, and the first flight to Europe (to Heathrow) followed on March 12, 2008.

Both companies have also entered into many cooperative agreements with aircraft and engine designers and with the suppliers of major airplane components in Europe, North America, and Asia, a reality that has done away with the formerly common pattern of a single-country origin. Both companies will also continue their duopoly in the market for wide-body and long-distance aircraft, but they now face a creeping competition from below as Bombardier (a Canadian company) and Embraer (Brazilian) continue to enlarge their commuter jets. Bombardier's first models (the CRJ-100), introduced in 1992, seated just fifty, and its latest (the CRJ-900) seats eighty-six. Embraer's smallest commercial jet (the EMB-135) takes thirty-seven people, and the EMB-195 can accommodate 108 to 122 passengers (Embraer 2009).

Reliable worldwide statistics regarding the performance of global aviation are available only since the late 1920s. In 1929, the world's airlines (excluding the Soviet Union) performed 96.3 million passenger kilometers (pkm), overwhelmingly on short- to medium-distance domestic routes using small-capacity piston-engine aircraft. A decade later, the introduction of higher-capacity planes (particularly the now iconic DC-3 in 1935, whose later version could carry up to thirty-two passengers; see [fig. 2.10](#)) and the first regularly scheduled transoceanic flights pushed the worldwide aggregate to 1.395 billion pkm; and by 1950, still without any commercial jetliners, the total reached 28 billion pkm.

During the second half of the twentieth century, commercial airline travel multiplied 123 times, from 30 billion to about 2.8 trillion pkm, and this

growth corresponded almost exactly to an average annual rate of 9 percent, doubling, on the average, in less than eight years (fig. 6.16). Only the first doubling was almost completely driven by aircraft with reciprocating engines. The rest is ascribed to the adoption and diffusion of jet engines. And even the tragedy of 9/11 did not stop further expansion. The growth rate moderated to just short of 6 percent per year between 2000 and 2005—when the aggregate reached 3.7 trillion pkm and when the world’s airlines had carried for the first time more than 2 billion passengers. And between 2005 and 2008, the passenger kilometer total rose by another 25 percent (or nearly 8 percent per year) to nearly 4.7 trillion pkm and to roughly 2.25 billion passengers (fig. 6.16).

Many economic benefits of modern air traffic have been quantified in detail and are conveniently summarized in the latest update of the Air Transport Action Group study (ATAG 2008). Its main findings credit the industry’s more than 3,200 airlines with generating about 32 million jobs (5.5 million directly) and a total economic impact (direct, indirect, induced, and catalyzed) of \$3.5 trillion a year (about 7.5 percent of the global economic product). But some important benefits elude simple quantification: modern aviation is the only means of a truly global travel that is essential for both business (25 percent of all companies’ sales depend on air transport) and leisure (40 percent of all international tourists now travel by air).

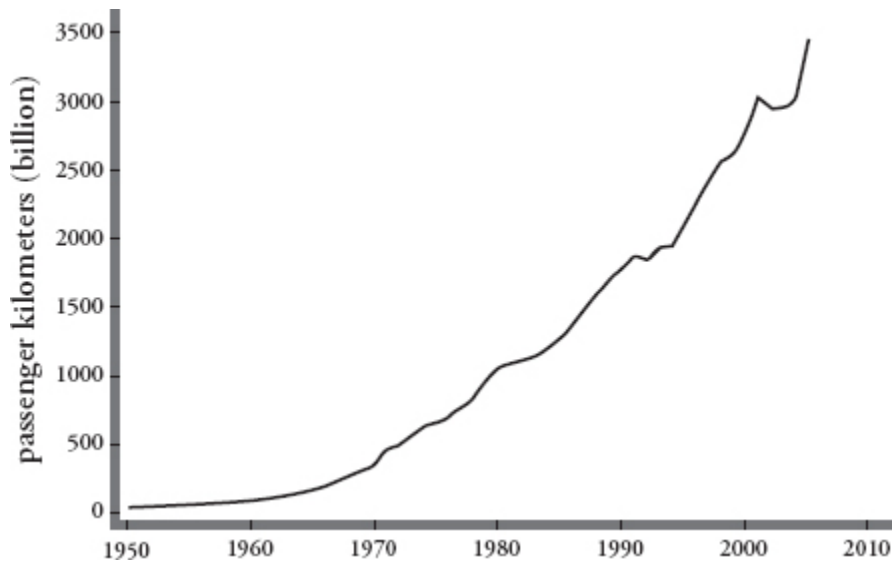


Figure 6.16

A semilogarithmic graph showing the exponential growth of passenger kilometers flown by the world's commercial airlines, 1950 to 2008 (plotted from data in annual International Civil Aviation Organization reports).

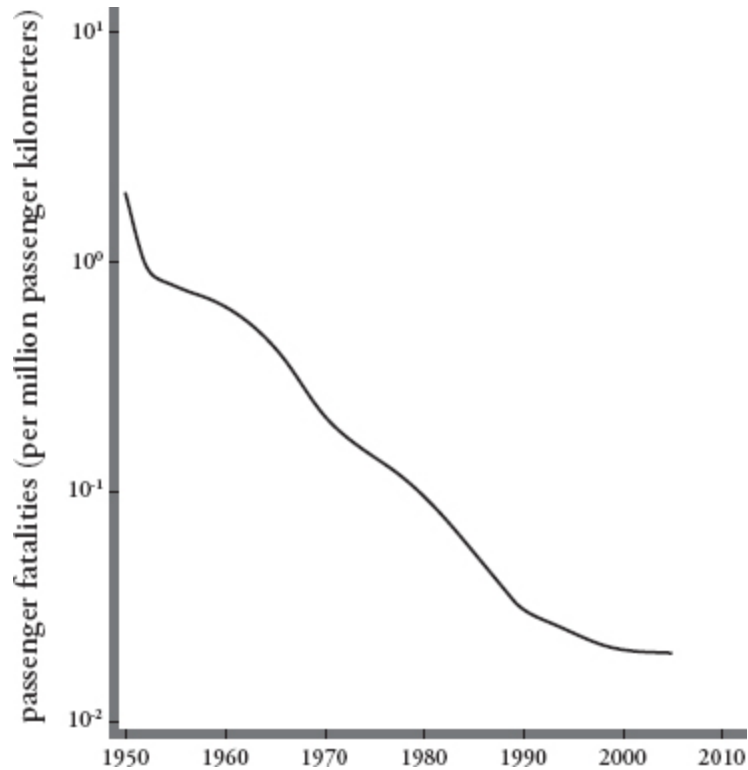
Expanding economies and higher disposable incomes drove the post-1950 demand for more air travel, and the constant additions of new scheduled flights (whether through the major hubs, such as JFK or Heathrow, or by more pairs of direct city connections) in more types of jet airliners (from commuter planes to wide-body intercontinental aircraft) have met it with room to spare. Peak time periods and some routes in high demand may see full, indeed overbooked planes, but even during the record-earning year of 2007, the industry's average passenger load factor was 77 percent. At the same time, average ticket prices adjusted for inflation have continued their post-1945 decline. For example, a round-trip economy-class ticket for the busiest trans-Atlantic crossing between New York and London (in constant 2005 dollars) fell from about \$6,000 in 1950 to \$2,000 by 1985 and \$600 by 2005. These intensifying (and more affordable) connections of people, countries, and cultures could be seen as the single largest benefit of air transport—its great intangible but invaluable contribution to the gradual, difficult, but perhaps inevitable formation of a truly global civilization.

Three specific measures serve as revealing indicators of the globalization of airborne passenger (and freight) traffic—the falling shares of the world market held by the U.S. companies that used to dominate the industry, the rising share of international traffic in general, and an increasing share of Asian traffic in particular. In 1950, the U.S. carriers accounted for more than 80 percent of all passenger kilometers. During the late 1960s, they still had half of the global total, but by 2005, their share was down to 33 percent (Intl. Civil Aviation Organization 2006). International flights accounted for less than 10 percent of the total pkm in 1950. By 1970, at the beginning of the second decade of the jet age, their share rose to 35 percent, and they surpassed 60 percent of the pkm total in 2007 (but in passenger terms, they were only 40 percent by 2008). Integration of the world's most populous continent into the global economy is reflected by the rising share of air traffic that is claimed by Asian carriers. One attribute of jet travel is even more remarkable than are its steady growth and overall magnitude—its outstanding safety. This safety is attributable largely to the extraordinary

high reliability of large turbofans, and as a result, jet-powered commercial flight is by far the safest mode of public transport.

In 1950 (with piston aircraft only), there were 1.97 fatalities per 100 million pkm. By 1965 (with the first generation of turbojets), the rate was down to 0.35, and since 1996 it has been below 0.05, with the 2005 rate at just 0.02 (fig. 6.17). In terms of accidents per million aircraft departures, the rate was in excess of fifty in 1960 (at the beginning of the jet age) but averaged just 0.89 between 1996 and 2005. Most of this low rate was due to human errors as less than 5 percent of it was attributable to either to a system or component failure or to engine malfunction. Nothing illustrates the reliability of large turbofans better than their contribution to the low accident rate of modern jet-powered travel. In the ten years between 1998 and 2007, the worldwide commercial jet fleet had fewer than two accidents per million departures (compared to twenty to thirty in the early 1960s)—and of the total of ninety fatal accidents that killed 5,147 people onboard during that period, only two (resulting in two fatalities) were caused by component failure or malfunction of engines (Boeing 2008a).

Another consequence of this reliability has been a routine use of twin-engine aircraft (mainly the Boeing 757, 767, and 777 and various Airbus planes) on routes where they are up to three hours (or even 207 minutes) from the nearest airport. Extended-range Twin-engine Operational Performance Standards (ETOPS) 180/207 opened up about 95 percent of the earth's surface for great-circle connections, leaving out only a small part of the western equatorial Pacific and the southernmost, near-Antarctic, portions of the three great oceans (fig. 6.18). In January 2007, the Federal Aviation Administration allowed U.S.-registered twin-engine aircraft to fly (with more stringent in-flight engine shutdown rates and with upgraded fire-suppression, oxygen supplies, and defibrillators) virtually everywhere except over the Antarctica, small parts of the southern Pacific, and the North Pole (FAA 2007).

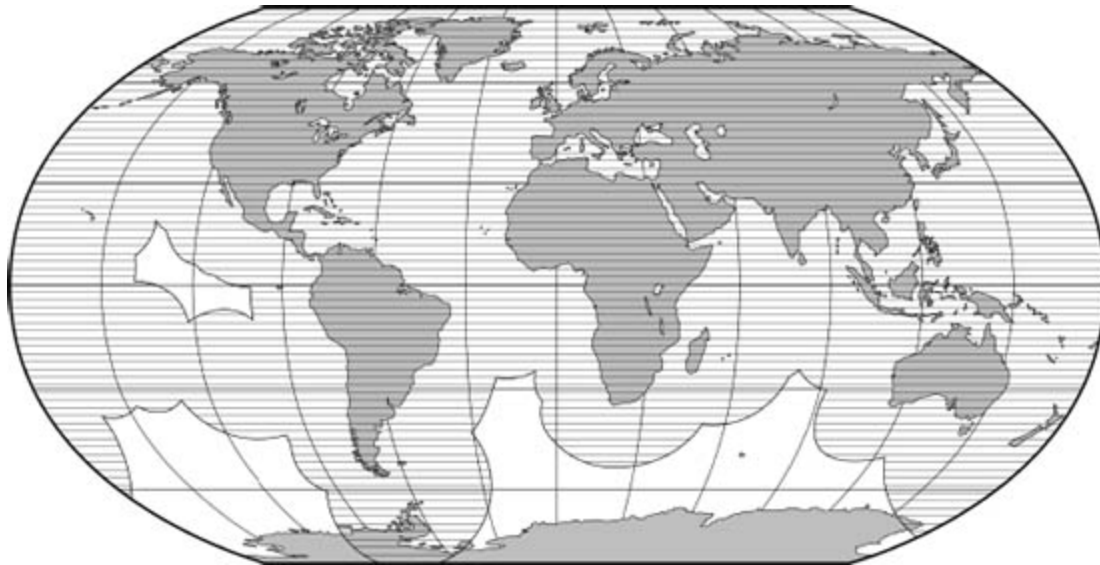


**Figure 6.17**

The safety of commercial flying: fatalities per 100 million passenger kilometers, 1950 to 2008 (plotted from data in annual International Civil Aviation Organization reports).

Mail was the first cargo transported in the small wood-frame airplanes that were used at the beginning of commercial flight in the early 1920s. As with many other advances, air transport got a large boost as a result of World War II, when U.S. aircraft factories made more than 9,500 DC-3 versions for the military (they were known as C-47 Skytrains). Many of these planes became available for commercial use after the war. Global air-cargo services totaled only about 750 million tkm in 1950, but by the year 2000, they were more than 143 billion tkm, and in 2005, they reached nearly 172 billion tkm (nearly a 230-fold increase) with nearly 90 percent of the total on international routes (Smil 2006; Boeing 2008b). High fuel prices slowed their growth rate in 2006 and 2007, and in 2008 the industry delivered less cargo than it did in 2007. In aggregate mass terms (with about 40 Mt airlifted in 2008), air cargo remains a tiny fraction (only about 0.5 percent) of the shipborne trade (some 8 Gt in the same year), but, as already noted, in terms of value airplanes carry about 35 percent of the interregional trade.





**Figure 6.18**

Extended-range Twin-engine Operational Performance Standards (ETOPS) 180/207 makes it possible for twin-engine jetliners to fly virtually anywhere in the world except in a small region of the Pacific and the southernmost latitudes (based on a map in Bachtel 2003).

Every long-distance passenger plane is also a cargo plane, and carrying goods accounts for 10 to 15 percent of its earnings. Every major airline also has dedicated cargo carriers (now mostly wide-body jets), and there are many specialized cargo companies. Wide-body passenger airplanes usually carry 10 to 20 tons of containerized cargo on long-distance flights, while dedicated cargo planes (mostly wide-body jets) transport 50 to 100 tons. In addition to such well-known commercial cargo fleets as FedEx or UPS, many specialized charter companies serve the global economy, as does the global-reach military.

The Boeing 747 is the most common international cargo carrier, but the Soviet-designed and now Ukrainian-produced Antonov 124-100 (*Ruslan*) can carry nearly 50 percent (up to 150 t) more. It is used to transport anything from heavy oil-drilling equipment to armaments for peacekeeping operations around the world (Volga-Dnepr Group 2009). Needless to say, the high energy intensity of air transport—around 30 MJ/tkm, or at least ten times the energy intensity of trucking and a hundred times that of railway transport—makes it suitable only for high-value items, and the service is subject to downturns brought on by high price of fuel or reduced economic activity.

Despite its overall revenue growth and its constant technical improvements, the global airline business has turned out to a largely money-losing proposition. Annual financial results for all of the world's airlines belonging to the International Air Transport Association (IATA) reveal that collectively they did not show any net operating profits (that is, after subtracting interest on loans and taxes) in six years in the 1970s, four years in the 1980s, and five years in the 1990s. Their only net profits in the first decade of the twenty-first century were in 2000 (about 1.1 percent margin) and 2007 (about 2.5 percent), and the prospect is for another string of loss years starting in 2008 (Intl. Air Transport Assn. 2009). The 2007 profit was made despite the rising fuel prices. In that year, they accounted for 28 percent of all expenses (in 2008, this rose to 32 percent), double the share in 2003. An inevitable result of this precarious situation has been the demise of many long-established companies, none more stunning than the end of Pan American Airways, which had been established in 1927.

In the 1930s, that pioneering airline became the chosen instrument of the U.S. foreign policy, and for decades it led the industry with its bold innovations—from the Pacific-crossing Clippers of the 1930s to the Boeing 747. But the company began unraveling in the 1970s and could not be saved even by the termination of its trans-Atlantic flights. The destruction of its flight 103 over Lockerbie, Scotland, in December 1988 (a bomb placed by Libyan agents killed 270 people) was the final blow, and the company ceased to exist three years later. Other major carriers that became defunct include America's Braniff and Piedmont and Europe's Sabena and Swissair, and the list of defunct smaller carriers contains scores of companies on both continents. In addition, virtually all of North America's major airlines have filed at least once for protection under chapter 11 of the federal bankruptcy code, but most of them emerged out of bankruptcy. That list includes United Airlines, Air Canada, US Airways, and Delta.

Not surprisingly, an industry that transports annually more than 2 billion people, that operates in every country, and whose machines overfly all of the earth's territories (with the exception of the southernmost parts of the Southern Ocean and Antarctica) has triggered concerns and apprehensions while providing admirable opportunities and valuable advantages. On both personal and collective levels, there have been increasing frustrations with overcrowded (even while forever expanding) airports, too few runways, overbooked flights, frequent departure delays (caused partly by overloaded

aircraft control centers), poor (or nonexistent) food, lost luggage, and irrational operating procedures. As *The Economist* put it in a June 17, 2007, editorial, air travel “is often nasty, brutish, long and unprofitable.” On the other hand, in 2008 Singapore Airlines began to offer “a privileged few” “their very own haven of tranquillity”—personal cabins with stand-alone beds and not converted seats—in “a class beyond first.” For some passengers, however, no amount of comfort will ever eliminate the effects of jet lag after arrival.

For a typical passenger, the names of many major international airports—London’s Heathrow above all, but also Rome’s Fiumicino, Paris’s Charles de Gaulle, New York’s JFK and La Guardia, and Chicago’s O’Hare—have become synonyms for stress and frustration. Although inexpensive intercontinental flights have made it possible to maintain family ties and have opened up unprecedented opportunities for journeys of leisure or private discovery, they have also helped to accelerate the worldwide movement of illegal migrants, facilitated far-flung operations of organized crime, promoted illicit drug trade and plane hijackings, and since 9/11 (through the use of airplanes as missiles) have been added to the most dreaded tools of international terrorism.

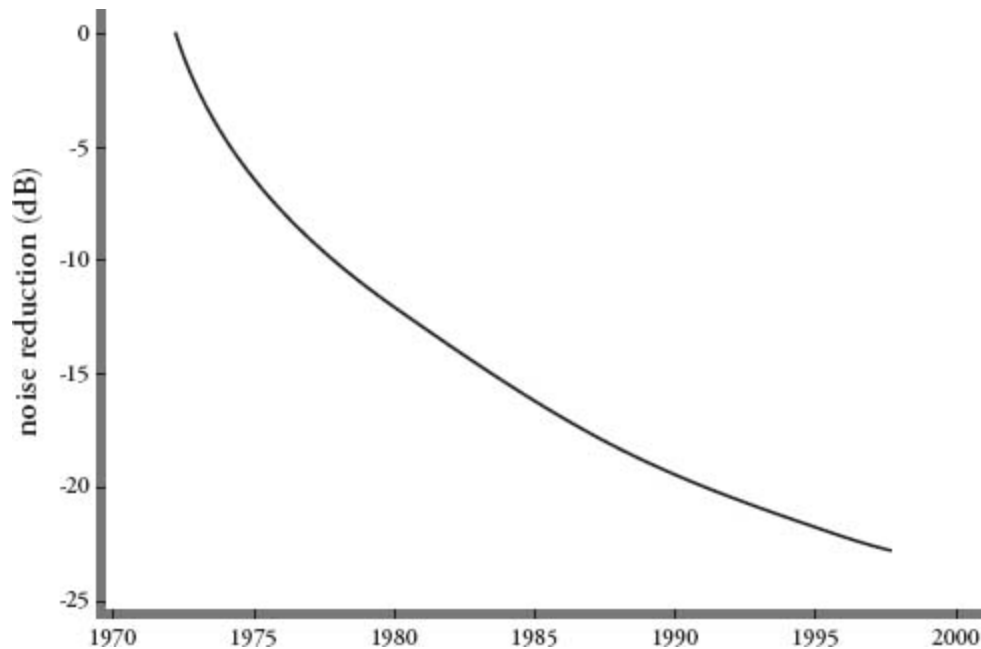
Given the makeup of the world’s current and future populations and their religious and economic divisions, it may take generations before we will not associate flying with terror and before we will be able to relax most of today’s airport security measures (many of them being of dubious efficacy). To this list of concerns must be added rapid intercontinental transmission of infectious diseases. This reality that was dramatically illustrated by the diffusion of the SARS pneumonia virus from Hong Kong to Toronto (Abraham 2005), and fears about a much more dangerous new influenza pandemic are justified by the fact that the annual flu epidemic is clearly spread by air travel (Brownstein et al. 2006).

Inevitably, increasing air traffic has become a notable contributor to anthropogenic atmospheric change (Intergovernmental Panel on Climate Change 1999). This has not been because of extraordinarily large absolute contributions to the global totals of greenhouse gases. Aviation contributes only about 2 percent of global anthropogenic carbon dioxide emissions, compared to 14 percent from road transport, and it is also a relatively minor contributor of nitrogen and sulfur oxides and water vapor. Nor is the comparison highly unfavorable when it is done in the terms of carbon

dioxide emitted per passenger kilometer. Long-distance flight is not much worse than a two-passenger gasoline-fueled car would be covering the same distance (Chapman 2007).

The concern is primarily due to the fact that thousands of jetliners emit these gases mostly into the upper troposphere, where conditions differ substantially from those near the surface. Although it does not matter where carbon dioxide (the dominant and long-lived greenhouse gas) is emitted, nitrogen oxide emissions are more effective precursors of ozone in the upper troposphere, it takes longer to eliminate sulfur oxides emitted at such altitudes, and the low air temperatures (around  $-50^{\circ}\text{C}$ ) at 10 to 12 km above ground result in the frequent formation of condensation trails. The long-term effects of subsonic flights near the edge of the troposphere include positive radiative forcing (atmospheric warming) due to carbon dioxide emissions, higher ozone concentration (due to the emitted nitrogen oxide), and water vapor in contrails—and negative radiative forcing (atmospheric cooling) caused by decreased concentrations of methane (due to nitrogen oxide) and small additions of sulphates (from sulfur oxide).

So far, the net effect of these processes has amounted to only 0.05 watt per square meter compared to the overall anthropogenic net radiative forcing of about  $1.8 \text{ W/m}^2$  relative to 1880 (Alley et al. 2007). But the atmospheric effects of air traffic are distributed very unequally, with the highest concentrations of emissions in the midlatitudes over the United States and Europe. Minnis et al. (1999) found that during the late 1990s contrails covered up to nearly 4 percent of the sky over the northeastern France and more than 5 percent in the vicinity of New York (whereas the global mean contrail coverage was not even 0.1 percent) and that those emissions produced local warming of up to  $0.7 \text{ W/m}^2$ —that is, thirty-five times the global mean contributed by water vapor from jet engines.



**Figure 6.19**

The reduction of noise generated by aviation gas turbines, 1972 to 1998 (based on Ballal and Zelina 2004).

Air-traffic-generated noise is the most common cause of public complaints by people living in the vicinity of major airports. Any nonsteady flow produces noise, but modern jet engines are particularly noisy machines because their blade speeds and flow velocities are close to the speed of sound (Cumpsty 2003). Most of their broadband noise comes from the turbulent mixing of the exiting jet with the surrounding air, with the jet noise being proportional to the eighth power of jet speed (it more than doubles, adding 3 decibels for every 10 percent increase in speed). Consequently, turbojets of the late 1950s generated more than 120 dB, with low-bypass-ratio turbofans the maxima fell to about 110 dB, and the latest high-bypass turbofans produce as little as 95 dB as far as both the lateral noise level (measured 450 m from the runway) and the approach noise level (referenced to the altitude of 120 m and 2000 horizontal m from the touchdown) are concerned (fig. 6.19).

Although these levels are below the maxima allowed by ICAO and FAA regulations (for comparison, a large truck diesel engine will produce 100 dB at a distance of 10 m), they remain not just a source of annoyance and discomfort. There is also a possibility that long-term exposure to high noise levels can be associated with increased cardiovascular mortality (van

Kempen et al. 2002). These concerns have led many communities to enact their own, stricter noise regulations. Besides lowering jet velocity by using higher bypass ratios, noise was initially reduced by installing silencers and later by lowering fan speed, increasing axial gap between turbines rotors and stators, and installing acoustic linings.

## Why the Two Engines Are Here to Stay

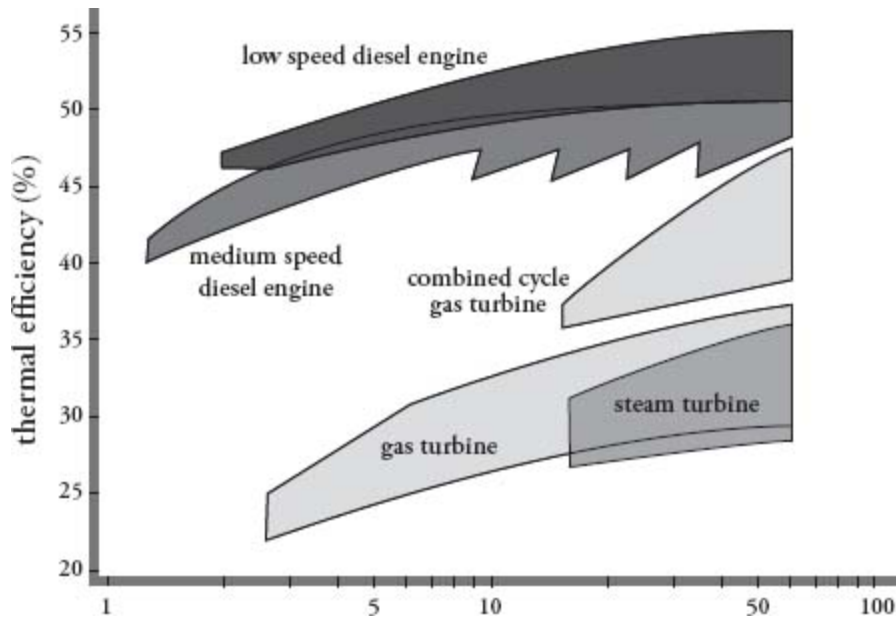
Frequency dependence occurs when a new technique succeeds because it has already been adopted by a sufficiently large number of users. This kind of model sounds at first almost discouraging, since in its strictest sense it means that only success succeeds, a blueprint for total stasis. Of course, such hurdles could and have been overcome.

—Joel Mokyr, *The Gifts of Athena*

A flippant answer to the question about the future of modern civilization's two key prime movers would be to repeat Joel Mokyr's summation of the frequency dependence in this chapter's epigraph. Because only success succeeds and because the commercial success of the two inventions has gone far beyond what even their creators dared to dream, the prospects for diesel engines and gas turbines are bright. If I had to select only two key attributes to explain both their ascendance and assured prospects, it would be their range of commercially available power ratings and their relatively high conversion efficiency. Both diesel engines and gas turbines are now available in versions ranging from a few to about 100 MW, and their conversion efficiencies approach or surpass 40 percent and (for low-speed diesels) even 50 percent, a combination that makes them superior to any alternative (fig. 7.1).

Moreover, their success has not been just a matter of relative accomplishment, remarkably broad capacity ranges, and markedly better performances than those offered by competing machines. The two engines have succeeded because they have offered truly incomparable combinations of other advantages. In this book, I have tried to demonstrate all of the key technical reasons for their remarkable achievements as well the multifaceted enormity of their consequences and influences, both in terms of their great benefits and unwelcome costs. My principal motivation for doing so has been to remedy, at least to some small extent, what is to me an inexplicable lack of attention paid to those machines whose true Cinderella

roles—doing virtually all the work of modern globalization with scant recognition—deserve much better understanding.



**Figure 7.1**

The power ratings and conversion efficiencies of steam engines, Otto-cycle gasoline engines, steam turbines, gas turbines, combined-cycle gas turbines, and medium-speed and low-speed diesel engines (based on a figure in Aabo 2007).

When examining the history of civilization by following the genesis and adoption of technical inventions and innovations, we should place the prime movers at the center of attention. Economic globalization has been studied from political, legal, financial, and cultural perspectives, with a great deal of attention paid to capital flows, labor costs, trade agreements, communication and information, and expanding standardization. But the two most important prime movers of the global economy have remained largely invisible, and it does not matter if they are actually hidden in the bowels of great ships or if they are mounted in plain sight as giant pods underneath the wings of jetliners.

The remarkable invisibility of prime movers can be illustrated in various ways. Who among educated adults has not heard about the endless rounds of global trade negotiations, who is not aware of the contending arguments regarding the consequences of free trade, who does not know (indeed, has not seen) a Boeing 747, the first wide-body jet? Who is not aware of Wal-Mart's China supply pipeline, and who has not seen the images of container



ships laden with what seem to be gravity-defying layers of steel boxes? But for how many people would the JT9D or the K98MC7 (the engines that have made those remarkable airplanes and vessels possible) ring any bell, and how many educated adults could cogently and accurately describe how a turbofan works (and why it is superior to a turbojet in commercial aviation) or why diesels endure?

As for the marine diesels, they get ignored even by people who write about longdistance shipping. Two recent books examined the genesis and diffusion of containerized shipping—but Levinson (2006) managed to do so without ever mentioning Diesel’s engine in 341 pages of text, and Cudahy (2006) devoted about two and half (of 318) pages to the transition from steam to diesel but had nothing to say about the remarkable advances in the development of diesels. Similarly, Stopford (2002, 4) concluded that cargo containerization “opened the floodgates for the development of the global economy,” and Tung Chee-hwa (whose shipping company was saved by Beijing loans in the 1980s and who became Hong Kong’s first chief executive under Communist rule in 1997) said that “without the container the global village would still be a concept, not a reality” (quoted in Stopford 2002, 4). Remarkably, even a former shipping executive saw no need to give any credit to diesels, reserving all of it for a steel box.

Ask your friends or colleagues this simple question: which human artifact would you remove from the modern world to return the global economy speedily into its pre–World War II stage? I can imagine all kinds of answers, but the diesel engine would be a very unlikely response. Most people would suggest computers or microchips, an erroneous conclusion whose prevalence was already noted at the outset of [chapter 3](#). The very ubiquity of diesels has been suggested as one of the reasons for overlooking their critical contribution. In a report prepared for the Diesel Technology Forum, a leading U.S. consulting company developed the notion of the diesel industry as an aggregate of activities whose contribution “to the U.S. economy goes largely unnoticed because diesel technology is so widely applicable and is used in many different types of equipment” (Charles River Associates 2000).

That definition of the diesel industry encompassed the diesel segment of oil refiners, distributors of fuel, and makers of engines, trucks, buses, ships, construction equipment, compressors, pumps, and generator sets. Based on the 1992 Economic Census, the value of produced goods and wages paid to

the workers who produce them added about \$85 billion, making the American diesel industry of that year larger than the nation's iron and steel sector or electronic components manufacturing and roughly the same size as all logging, milling, and wood processing.

The importance of Diesel's engine in the modern transport of goods can be also traced by comparing sectoral statistics that have been available for the United States since 1939 and that measure the overall performance as a product of mass and distance (that is, in tkm). In 1939, railways (which at that time were still dominated by steam engines) accounted for just over 70 percent of all freight (excluding pipeline transportation), waterborne transport (already mostly diesel-powered) was second with almost 20 percent, and trucks (many still running on gasoline) were third with 10 percent (U.S. Census Bureau 1975). This means that by the late 1930s, diesel engines powered only about a third of the country's intranational freight movement. By the early 1970s, the railway share fell to just below 50 percent, the trucking share more than tripled, and there has been little change since that time. By 2005, 49 percent of all U.S. freight was carried on rails, a third on roads, 17 percent on river and coastal barges and ships, and less than 0.5 percent by airlines (U.S. Census Bureau 2009). With most freight trains, all vessels, and virtually all trucks powered by diesels, this means that more than 95 percent of all U.S. freight now moves thanks to Diesel's engines.

There can be no better example of the effects of more affordable shipping and air transportation than the post-1960 economic development of New Zealand, an isolated economy whose small size makes it particularly challenging to take advantage of the economies of scale that are available to the European Union, the United States, or Japan. BOAC launched its jet service from London to Auckland in 1963 (with a de Havilland Comet and two years later with the Boeing 707). The wide-body Boeing 747 and DC-10 followed soon after, and by 1980, the flight from Auckland to Sydney cost a quarter of what it did in 1970 (Rennie 1990). Limited container shipments to New Zealand began in 1971, and by 1980, all of the country's substantial frozen meat shipments to the United States came in refrigerated containers. This process, carried initially (and often not very efficiently) by state-owned enterprises, accelerated after 1984 with deregulation and privatization. Waite (2004, 1) concluded that it "quickly reduced the cost of distance, accelerating the globalization of New Zealand."

Although the roles played by the two efficient and reliable prime movers were critical, contributions were made by other technical and nontechnical factors that have been driving the process of economic (and even social if not yet political) globalization. *Globalization* became a commonly used (and multiply loaded) term in the 1990s when the media, governments, nongovernmental organizations, and activists of all kinds offered their widely differing appraisals of the process—ranging from enthusiastic endorsement to passionate condemnation. But as is shown in this book's opening chapter, the process itself is old, predating the age of simple machines by millennia. The beginnings of interregional trade go back to prehistory.

True globalization began during the early modern era, when trade was restricted to only a few segments of the economy and benefited only the most affluent inhabitants of a few trading countries. The process reached a critical mass in the last generation of the nineteenth century, was then interrupted and set back by the great wars and the global economic depression, and entered its rapid and eventually virtually all-encompassing stage in the 1950s. Greatly expanded imports of crude oil to Europe and Japan and rising trade in inexpensive manufactured products (especially apparel and toys) were its first drivers, and they soon were joined by more diversified agricultural exports, cars, and electronic products.

By the 1990s, the process of attendant specialization and product concentration reached such unprecedented levels that entire classes of globally sold common consumer products originated in a surprisingly small number of highly specialized labor-intensive assembly plants or in highly automated fabrication facilities. The two subjects of my inquiry provide perfect examples of this trend toward a high degree of concentration. By now, readers of this book appreciate that just three companies (General Electric, Pratt & Whitney, and Rolls-Royce) and their alliances supply all of the world's jet engines and assemble these in fewer than twenty facilities in half a dozen countries. All of the world's massive low-revolutions-per-minute, high-power marine diesels are either MAN (incorporating B&W) or Wärtsilä (incorporating Sulzer) designs that are now most likely built in South Korean or Japanese factories.

But neither the long genesis of the globalization process nor its current extent can guarantee its continuing intensification. The process can slow down or can be reversed—much like the supposedly unstoppable triumph

of communism or, to chose an opposite and painfully recent example, the dazzling march of the new economy (exemplified by the rise of NASDAQ). After all, in the 1930s the world economy was much less globalized than it was at the century's beginning and not just because the U.S. Congress passed the highly protectionist Tariff Act of 1930 (the Smoot-Hawley Act): by 1934, world trade was down by two-thirds compared to 1929.

Even if the performance and cost of its prime movers were of no concern, continued globalization has its obvious physical limits, including resource availability and various infrastructural considerations. The peak of conventional global oil extraction may not be only a few years away (as is anticipated by the proponents of an imminent peak oil production), but it is very likely to come by 2020 or 2030 (Smil 2008; Kerr 2008). Long before it arrives, it will be signaled by permanently elevated crude-oil prices that will make diesel fuel and kerosene significantly more expensive. Because the potential substitutes (biofuels and liquids produced from solids or gases) are unlikely to be less expensive, such a change would make all long-distance shipments less rewarding and would inevitably curtail the frequency of both business and discretionary flying.

Should the real costs of refined liquid fuels triple or quadruple (and stay at those levels), long-distance shipping of expensive, high-value-added products might remain largely unaffected, but such high and lasting cost increases would definitely limit any further expansion, if not the continuation, of importing inexpensive, machinemade goods from other continents. As far as food is concerned, the dependence on distant markets (although Gilroy, California, styles itself as the garlic capital of the world, virtually all of America's dehydrated garlic and all but a small fraction of fresh bulbs now come from China) has already led to increased concerns about the safety of supplies and to calls for a greater reliance on locally or regionally produced food (Halweil 2004). With very expensive fuel, it would not make sense to ship out-of-season fresh fruit (after all, it is more than 90 percent water) to distant continents and, because people expect the fruit to arrive unblemished, to spend more energy on cooling it along the way.

Infrastructural limits (such as the depths of ports and canals) already restrict the size of the largest vessels on many intercontinental routes, and they have also become more prominent with the continuous expansion of air traffic. Except for a few new installations, the existing arrangements

(including airport terminals, runways, control systems, landing rights, and security) cannot meet even today's demand, resulting in an unprecedented share of delayed and canceled flights and in compromised safety. Given this reality, it is difficult to envisage a several-fold increase in the overall passenger count without massive new investment and major technical fixes, but neither appears to be imminent.

Economic globalization cannot ignore public opinion. The reactions to the power of global business (commonly perceived as excessive and insufficiently regulated), the disappearance of cherished traditions (regardless of the fact that some of them were of questionable worth), and the dominance of entire market segments by products from other continents have included resentment, local opposition, and a resurgence of nationalistic feelings, and their political and social consequences should not be underestimated. Indeed, Japan's large trade surpluses with the United States during the 1980s triggered such angry reactions among some politicians that all Japanese automakers decided to make most of the cars they sell in North America in the United States and Canada. Most of their profits still go across the ocean, but millions of cars do not—yet another illustration of the limits of globalization (in this case, the ending of the annual transfers of millions of vehicles by large roll-on roll-off vessels from Japan to North America).

The expectations created by the rising globalization of trade and travel are both understandable and problematic. Affluent consumers (and richer urbanites in low-income countries) now take it for granted that basic manufactured goods should be fairly inexpensive (and in terms of average purchasing power, actually progressively cheaper) and that they should have access to an unprecedented range of foodstuffs and products. The producers of these goods for distant markets (whether Chinese assemblers of toys and laptops or Chilean or South African growers of grapes and pears) have come to expect that their output will continue to be in demand in ever greater quantities. Leisure and business trips on an intercontinental scale have become routine for hundreds of millions of travelers, resulting in previously unthinkable personal experiences and productive ventures, and airlines anticipate further large increases of their aggregate passenger and cargo capacities. The beneficiaries of the process expect its rewards to continue, but they do not appreciate how fragile this arrangement is and how impermanent it may turn out to be in the long run.

The global economic recession of 2008–2009 offered an excellent example of sudden reversals: as the economies retreated and new orders declined, shipping rates plunged, empty containers piled up in harbors, tanker leases were not renewed, and plans for new infrastructural expansion were shelved. For some commentators these were clear indicators that globalization is a cyclical phenomenon and hence “vulnerable to terrible and costly backlashes,” and because so much of its recent expansion was driven by financial flows, the financial meltdown was judged to be “a very serious setback” (James 2009, 10). Naírn (2009, 11) countered this by admitting that economic globalization will be curtailed by the 2008–2009 financial crash but rejecting the claim that globalization is cyclical: “Surely, global integration ebbs and flows . . . yet, when one takes a longer historical view . . . the more permanent trend is one of continuous ascent. In the long run there is always more globalization, not less.” I completely share his view.

As for the periodic ebbs, flying is particularly sensitive to changed economic fortunes because people in affluent societies spend roughly constant shares of their disposable income (as well as of their time) on trips (Schafer 2003). In the European Union, that share (between 12 and 14 percent of all household expenditures) has remained fairly stable since the 1970s (Eurostat 2007), and if that share were to be maintained in stagnant or declining economies, long-distance flying would be the first mode of discretionary transport to be reduced. This means that airlines (and turbine and plane makers) feel uneasy when incomes begin to stagnate, and when they go down a notoriously vulnerable industry becomes even less profitable.

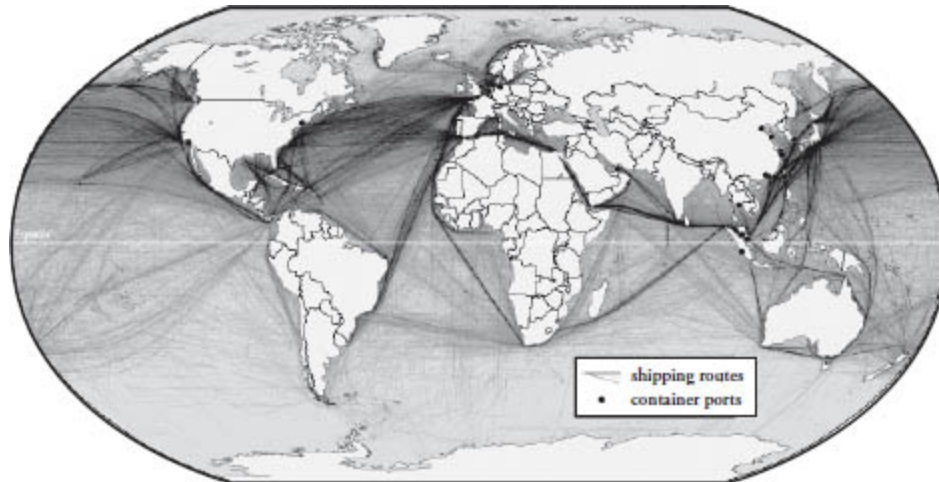
The eventual and unpredictable outcome of all of these influences could range from the further progress of economic globalization (enhanced or attenuated) to a significant reversal of recent trends. But I am not offering any quantitative point forecasts and do not have to be concerned about such (albeit critical) particulars. I can assert, with confidence, that the two prime movers will retain their dominant roles *regardless* of any particular configuration that the world economy (and hence its degree of globalization) will assume a decade or a generation from now. The possibilities include a gradual resumption of a vigorous globalization trend (most likely at a slower pace), deglobalization (a prognosis argued by Simon Johnson, a former chief economist at the International Monetary

Fund), or even an outright collapse of that remarkable phenomenon (as feared by Jeffrey Sachs).

Even the most extreme (and the least likely) outcome would not result in the cessation of international trade and travel, and the prime movers of these two world-spanning activities will remain the same for decades to come. Diesel engines have already accumulated seven decades of prime-mover primacy in intercontinental ocean transportation, and gas turbines have entered the sixth decade of being the sole prime mover of long-distance flight. In neither case are any technically outstanding, commercially viable replacements on the near- to midterm horizon.

### **Enduring Diesels**

The reasons for my confidence regarding the continuing indispensability of diesels in marine and land transport and gas turbines in flight are numerous, and the success noted in this chapter's epigraph is not the least among them. I start this concluding appraisal with diesels, and it may be apposite to relate (once more and in a yet different manner) the extent to which those engines have come to dominate the globalized economy and the degree to which they have transformed international trade. Nearly 100,000 ocean-going commercial ships above 100 dwt are now used to transport goods ranging from bulk commodities to containerized cargo. All but a tiny share of all these vessels (about 3 percent relying on steam turbines) are powered by diesels, and all of the largest ships are run by low-rpm two-stroke diesel giants with rated capacities in excess of 50 MW or even 80 MW. Besides steam-driven ships, there are also smaller gasoline-powered trucks that are engaged in shorter cross-border hauling so that when measured in tons per kilometer about 94 percent of global trade is now diesel-powered, and that very high ratio is still growing.



**Figure 7.2**

The areas of the ocean with the highest density of diesel-powered maritime traffic (based on a map in Kareiva et al. 2007).

While diesel-powered maritime shipping is a truly global affair, most of the regular commercial connections are in the Northern Hemisphere. Within it, the highest concentrations of vessel traffic are in coastal European, North American, and East Asian waters; along the trans-Pacific routes between Asia and North America; along the the trans-Atlantic routes between North America and Europe; and along the shorter (through the Suez Canal) and the longer (around Africa) routes between Europe and Asia (Kareiva et al. 2007; [fig. 7.2](#)). Such a high level of dependence (recall that ships now move annually more than 8 Gt of cargo and that return trips of 30,000 km are not unusual) cannot be altered easily or rapidly. In that sense, the future advances or retreats of economic globalization are irrelevant. The future growth of global trade may slow down, its aggregate value (whether in total value or in tkm) may even shrink appreciably, but whatever its eventual volume a decade or a quarter century from now, it will be carried almost solely by diesel-powered vessels.

There are, of course, many constraints on the speed and extent of any conceivable retreat from globalization. In ten or fifteen years, the United States could be experiencing a partial manufacturing renaissance that would lower the share of manufactures that are now brought from China. But during the same period of time, there will be no fundamental change in global dependence on Middle Eastern oil. Export shares may shift a little, but the countries around the Persian Gulf will still contain at least 60 percent of the world's remaining crude-oil reserves, and scores of countries



without any (or with inadequate) hydrocarbon resources will continue to rely on those very-large crude carrier shipments from Saudi Arabia, Iran, Iraq, Kuwait, and the United Arab Emirates.

Similarly, economic cycles will keep boosting and lowering demand for minerals, but Australian coal, Brazilian bauxite, and Chilean copper will always be delivered by large dry-bulk carriers to other continents. Although the expansion of liquefied natural gas projects may not proceed as fast as has been recently anticipated, there is no doubt that within twenty to twenty-five years there will be a much larger and a truly global market for the liquefied gas carried by increasingly larger tankers. Even if sub-Saharan Africa improves its food production, there will be continued strong demand for the two principal feed grains (corn and soybeans) that are shipped in large dry-bulk carriers.

Although the future of many bulk shipments may appear to be fairly assured (even as their aggregate totals will be subject to unpredictable economic downturns and upswings), some observers have argued that the high crude-oil prices experienced during the first half of 2008 were a clear sign of the coming reversibility of globalization based on containerized shipping (Rubin and Tal 2008). The transport costs of fast container ships are much more sensitive to the high prices of fuel than are the costs of relatively slow tanker shipments, and high oil prices of the first half of 2008 translated into an equivalent of nearly 10 percent the U.S. tariff rate compared to the equivalent of just 3 percent in 2000 (when the oil prices were just \$20 per barrel). At that time, it cost about \$3,000 to ship a container from Shanghai to the U.S. East Coast, but by the spring of 2008, that cost rose to \$8,000.

We have a telling historical experience with what happens when transport costs soar. Although the ratio of exports as a share of the global economic product rose by more than 50 percent between 1960 and 1973, the two subsequent rounds of OPEC-driven oil price increases (1973 to 1974 and 1979 to 1981) resulted in no further increase of world exports as a share of global economic product despite the concurrent 25 percent reduction on global tariffs. The ratio's growth resumed only in 1987 after oil prices fell dramatically in 1985 and 1986. Even so, the long-term consequences of higher fuel prices may not be crippling.

The higher that prices rise, the more likely is their precipitous collapse. In July 2008, as the NYMEX oil price approached \$150/barrel, many

thought that a price of \$200/barrel was inevitable before the year's end and that shipping a container from Shanghai to Newark would soon cost about \$15,000. Instead, oil prices fell rapidly, with the NYMEX rate averaging just over \$41 in December 2008 (returning to the level that prevailed in 2004), and by that time, the charter rates for container ships fell to all-time lows, below the level of the bear market of the early 2002 (Barnard 2008). Moreover, many Chinese companies sell their products on a free-on-board (FOB) basis, and hence their production costs are not affected by rising transportation costs. Such leading importers as Wal-Mart and Home Depot can recoup part of their higher shipping costs by squeezing their shippers. With many the shipping costs of mid- to high-price items equivalent to 4 to 6 percent rather than 2 to 3 percent of the retail cost, this would not be a reason to stop importing.

Perhaps most fundamentally, major Western companies—after investing collectively more than \$1 trillion in more than two decades of building China's vast manufacturing capacity in just about every class of common consumer products—could not quickly move their production from China. The aggregate volumes of various Chinese manufactures have become too large to be produced in a matter of months or a few years in new facilities that would have to be set up in North America and Europe. Although transportation costs would decline, labor cost would rise, and many economies of scale (with China now serving the global market) would be much reduced. There is no doubt that there could be (and I would argue that there should be) a considerable renaissance of North American manufacturing, but such a process would be a gradual matter. Finally, in the broadest economic perspective, any concerns about higher shipping prices pale in comparison with what the world economy began to experience in 2008: frozen credit and a global recession are infinitely greater worries than are higher shipping rates.

The conclusion is clear. Some ingredients of what lies ahead for the global economy may be perceived with confidence but in only in the most general terms. These include the continuation of either low population growth or outright declines of absolute numbers among most of the affluent nations and the gradually increasing role of the large modernizing economies of China, India, and Brazil. But specific national or global outcomes arising from complex combinations and interactions of many relevant demographic, economic, and political trends will be as elusive as

ever—and so will be the predictions of any pinpoint timings (will China become the world's largest economy by 2025? will the euro become the world's reserve currency by that time?).

This is why I abstain from offering any quantitative point forecasts regarding the total numbers of marine diesel engines, their overall or average unit capacities, or the future sizes of tanker or container-shipping fleets. Those eager to see such forecasts will find no shortage of published materials but will also readily notice their questionable value. Most published forecasts are in the category of traditional linear protractions of past experience modified by suggesting somewhat lower or higher growth rates. For example, the U.N. Commission for Trade and Development's 2008 forecasts of doubled container traffic by 2016 and of the total of some 370 million twenty-foot equivalent units (TEUs) shipped by 2020 (compared to 143 million in 2007) seemed too high even before the year 2008 ended as the global economy became caught in a recession whose extent and intensity were the worst since the Great Depression of the 1930s.

Whatever those specific parameters may be in a decade or a generation, diesel engines will retain their dominance in powering the global trade. It is not just that the marine diesel engines are simply too numerous and too ubiquitous to be replaced by a new prime mover in a short period of time. Steam turbines (used in conjunction with nuclear reactors to propel America's large aircraft carriers) and gas turbines (used on fast ferries and on military vessels ranging from gunboats to destroyers) are two well-tested and well-performing alternatives that are suitable for some maritime applications. But neither offers a superior performance (neither has reached efficiencies of large marine diesel) or a more desirable tradeoff between expected benefits and unavoidable costs.

The cost, efficiency, reliability, and durability of diesel engines offer a combination that has not been surpassed by any other energy converter. Even if a new candidate for substitution were to emerge soon, we must remember that energy transitions—whether they involve shifts to new fuels or shifts to new prime movers—are inherently slow processes whose time spans are measured in decades, not in years (Smil 2008). After all, diesel-powered ocean-going vessels became common only in the 1930s, some four decades after Diesel completed his design work in 1897. It took nearly fifty years for diesel-electric locomotives to equal the rated power of the steam

locomotive during its time of peak performance, and diesels have yet to conquer the passenger-car market in North America.

Nor are there any great prospects for changing the fuel used by the engines. Diesel himself, after extensively testing his invention with just about every possible fuel, demonstrated that his engine could easily run on oil pressed from plants, but the recent interest in biodiesel (liquid fuel made by the transesterification of plant oils) is more a fashionable demonstration of making everything “green” and “sustainable” than the beginning of a viable alternative. As with any biomass fuel, the power density of biodiesel production is very low, an inevitable consequence of the low efficiency of converting solar radiation to new phytomass and then using only a part of it (lipids are only about 17 percent of the total phytomass in soybeans and up to about 47 percent in sunflower seeds) for the conversion to a fuel.

The power densities of biodiesel production (energy harnessed annually per hectare of cultivated land) are thus very low, even in comparison with the crop-derived ethanol, whose production uses more abundant plant carbohydrates (Smil 2008). Brazilian sugar-cane-based ethanol is produced with power densities of up to  $0.45 \text{ W/m}^2$  of farmland, and American corn-based ethanol has yields of about  $0.25 \text{ W/m}^2$ —but biodiesel made from palm oil yields just  $0.1 \text{ W/m}^2$  of plantations, and the yields of biodiesel from sunflowers and soybeans are at best  $0.015 \text{ W/m}^2$ . This means that maritime transportation (whose annual fuel demand is about 370 Mt) that is powered by palm-oil-derived biodiesel fuel would require about 450 Mha of oil-palm plantations, about forty times their current extent of 11 Mha, and nearly a third of the world’s land used for annual or perennial crops (Food and Agricultural Organization 2009). Producing most of that biodiesel from temperate oil crops would need an order of magnitude larger area, easily surpassing the global total of 1.5 Gha of all cultivated land. Consequently, there is no realistic possibility of converting most of today’s maritime traffic to biodiesel.

Although there can be no single date marking the commercial maturity of diesel engines, it is easy to conclude that the years 1910 to 1912—when the total capacity of diesel engines in operation or under construction passed 1 million bhp and when the *Selandia*, *Fionia*, *Fram*, and *Christian X* began to demonstrate the superiority of diesels in maritime transport—were the undeniable beginning of a widely recognized success and enormous prospects. This means that we are about to enter the second century of

diesel-powered shipping. Remarkably, after it has gradually conquered all but a tiny share of its potential market, the engine's place remains secure as the least expensive, most reliable, and most powerful prime mover of goods, bulk or packaged, by ships or by trucks (it has an appealing alternative in electrified trains).

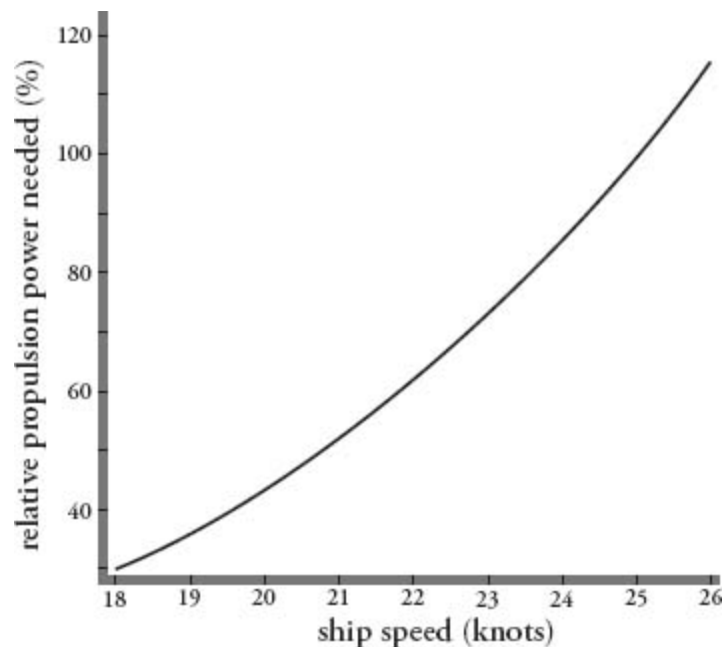
These realities mean that diesels will continue as the dominant prime movers of the global economy for generations to come. But it does not mean that the ratings of the largest diesels have to grow as much as they have in the recent past as there is no compelling case for building much bigger marine diesels. The typical sizes of the largest ships (whether oil or dry-bulk tankers) are not expected to increase substantially during the next ten to fifteen years, and even if they were to grow by 30 to 50 percent, the existing engines would easily provide the requisite propulsion. Today's largest engine sizes (approaching 100 MW) are not in service because they have to power extraordinarily large ships but because they have to provide speed for large container vessels. Consequently, today's engine could easily propel even larger container ships if those were to operate at lower speeds or if they had two propellers instead of a single directly driven unit.

More fundamentally, when thinking about the future growth of diesel engines, it should be remembered that the "size in itself is not an objective. It is a question of getting the right engine for the purpose" (Grøne 2006, 2). Engine designers have had an impressive record of getting more power per cylinder while reducing the specific mass-to-power ratio. As has been shown by MAN Diesel ratings, the output per cylinder has gone up by about 60 percent since 1982, while the specific weight declined by about 45 percent. This means that an engine with a higher piston speed that works with higher mean pressure can develop roughly the same output as an engine that is one bore larger. The potential for further improvements is still far from exhausted, and future engines may develop at least 10 percent and as much as 25 percent more power without any increase in size compared to today's commonly deployed models.

The challenge ahead is thus not to chase ever higher ratings but to make diesel engines even more efficient, more reliable, and more environmentally acceptable. No other measure can make such a difference as reducing the speed of maritime shipping, particularly in the case of fast container vessels. Reducing their speed from today's design levels of 25 knots to 21 knots would halve their power requirement, and a 20 percent speed

reduction for the entire fleet (dominated by many slower vessels) would reduce fuel demand by 40 percent (fig. 7.3)—that is, by about 150 Mt/year at the 2008 rate of consumption, more oil than used every year by India or Russia. Combining this reduction (which could be introduced in semiannual or quarterly 5 percent increments over the course of a few years) with new silicone-based hull coatings (preventing heavy biofouling and hence reducing friction and increasing ship speed by up to 10 percent) and with better hull designs would allow the industry to cut its current fuel demand by half.

Besides improvements in specific fuel consumption, the future development of diesel engines will also explore such hybrid technologies as the combination of diesels and electric motors. More work will be done on advanced turbocharging and on the uses of fuel-water emulsion (desalinated water mixed with fuel to provide internal cooling in the combustion chamber) to lower the formation of nitrogen oxide. And all diesel users will be under a greater pressure to use fuels with lower sulfur content, perhaps no more than 1.5 percent sulfur in general and less than 0.5 percent in areas that already have some fuel-quality restrictions in place (such as the Baltic and the North Sea).



**Figure 7.3**

The average speed and relative power requirements and fuel consumption of large cargo vessels (based on graphs in MAN Diesel 2009).

One emerging technical advance will not have any direct effect on marine diesels but can eventually change passenger cars worldwide and thus introduce a new dynamism into a key sector of the global economy. This recent development is the ingenious DiesOtto design by the Daimler Engine Research laboratories (Kohler 2008). The new engine starts by the spark ignition of directly injected gasoline and runs in this conventional (Otto) mode at full load. During partial load (that is at the low and medium speeds that are most common in typical driving), it morphs into self-igniting (diesel) operation. The engine is also supercharged. This combination means that an engine with fewer cylinders and with a smaller displacement offers great performance, low fuel consumption, and very low nitrogen emissions. Daimler's goal of making a gasoline engine that is as economical as a diesel is thus well within reach, and it is realistic to expect future DiesOtto machines to achieve more than 60 miles per gallon, above the rate for the today's highest-rated hybrid car (the Toyota Prius, which operates at 55 mpg for the combined city-highway cycle).

As the centenary of Diesel's death approaches, his engine belongs to those modern prime movers that have had the most profound impact on the course of the global economy and that have enabled many fundamental shifts in the everyday lives and expectations of billions of people. Gasoline engines and steam, water, and gas turbines are the other entries in this small category. All of them have served us well for generations, some for more than a century, and all of them will be with us for at least several decades, and some for generations to come. Beyond that, it is much harder to predict whether diesels, now just entering the second century of their commercial success, will be important prime movers at the beginning of the twenty-second century. Those who believe in an early onset of global peak oil production would curtly dismiss such a thought. I remain agnostic, always mindful of the remarkable inertia of reliable and efficient prime movers.

## **Future Aeroengines**

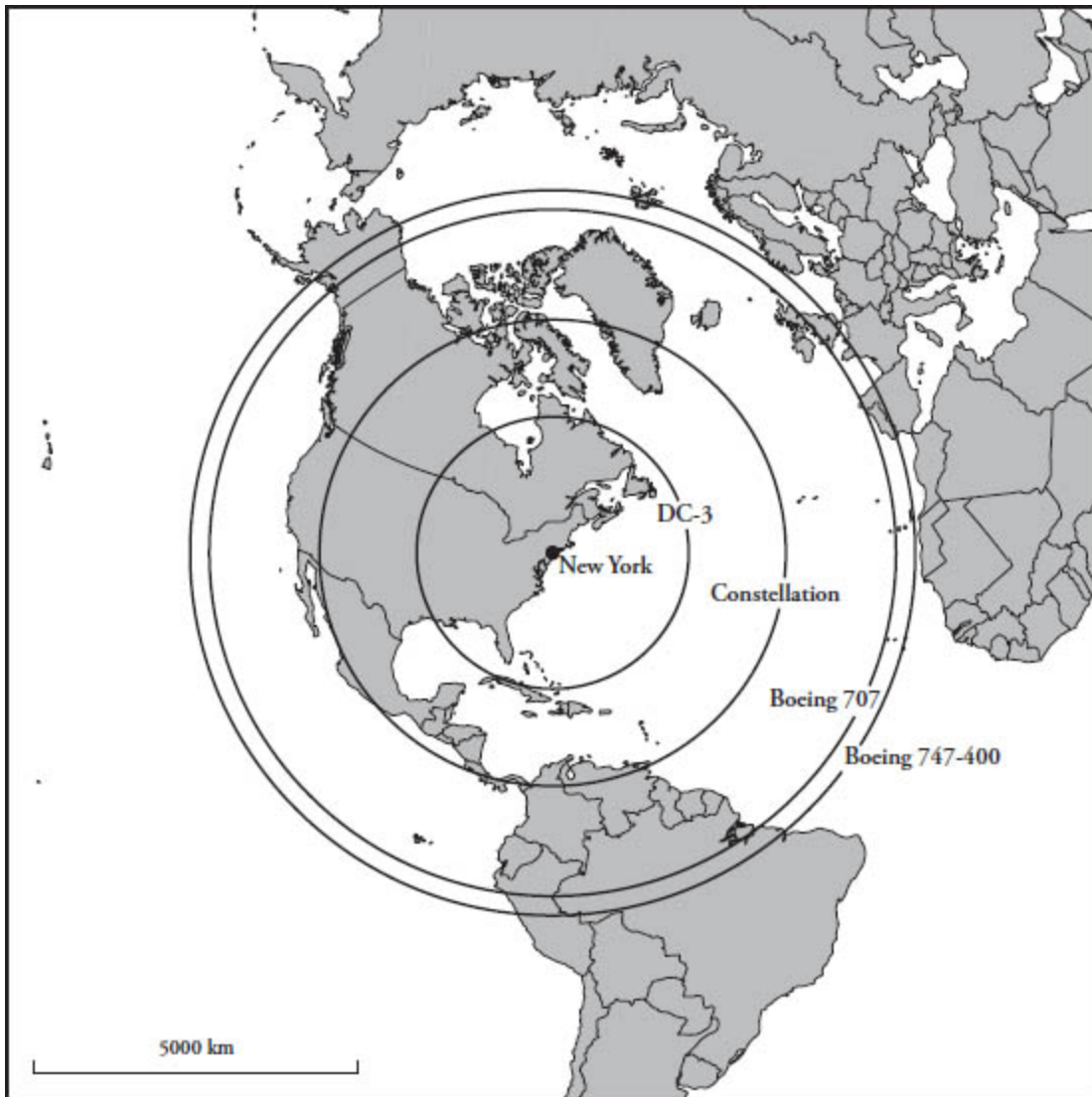
Assessing the near- and midterm futures of gas turbines in flight is an easier task because the jet-powered long-distance flight presents a clearer case of an unrivaled dominant prime mover than do diesels in maritime shipping. Without a single exception, all airplanes on interregional, transcontinental, and intercontinental routes are powered by large turbofan engines. There is

simply no practical alternative in sight if those long-distance journeys are to be accomplished at comparable speeds and in similar comfort. We could convert portions of those fast container ships into passenger compartments (and do so relatively easily if the accommodations were fairly basic) and move people among the continents even as we transport electronics, clothes, and toys to their markets, but a trip from New York to London on the fastest, large post-Panamax vessel would take more than five days, and a trip from Los Angeles to Tokyo would last thirteen days.

We could build a dedicated fleet of passenger ships that are powered by aeroderivative gas turbines. Their different designs (most prominently General Electric's LM2500 and LM2500+) have been used on many cruise ships (traveling up to 30 knots or about 55 km/h) and on a variety of fast navy vessels (including destroyers, cruisers, and frigates whose top speeds are around 40 knots, or close to 75 km/h). This option would lead to large gains in specific fuel consumption per passenger kilometer. But even if the average speed were to be 35 knots (65 km/h), such seaborne travel would reduce the length of trips taken at container-ship speed only by about 40 percent, so it would take still eight days to cross the Pacific from the West Coast to northeast Asia.

Here is one more reminder of what gas turbines have done for us. This map of the world is centered on New York, and circles mark the farthest ranges that could be reached by flying for six hours in two piston-powered airplanes—the DC-3 in 1940 (with an average cruising speed of about 275 km/h, this was the plane's maximum range), the Constellation in 1950, the turbojet-powered Boeing 707 in 1960, and the turbofan-powered Boeing 747-400 in 1990 (fig. 7.4). In 1930, there could be no such thing as a nonstop trans-Atlantic commercial flight. In 1950, the crossing took twelve hours, in 1958, it could be made—for the first time and, given the small number of the first-generation jetliners entering the service, by a limited number of passengers—in six. By 1960, it became an increasingly common event, and so, figuratively, the world shrank by half in a single decade.





**Figure 7.4**

The maximum ranges for six hours of flying from New York in a DC-3 (1940), a Constellation (1950), a Boeing 707 (1960), and a Boeing 747-400 (1990). Distances are calculated by using the average cruising speeds of the four airliners.

Since that time, jetliners have switched from turbojets to turbofans, bypass ratios and overall turbine pressures have gotten higher, and specific fuel consumption has declined (and so has generated noise), but cruising speeds have not changed. The pioneering Boeing 707 cruised at 870 km per hour (Mach 0.8) in 1958, and fifty years later, the superjumbo Airbus A380 cruises at 900 km/h (M 0.85). There were two costly attempts to change that—the supersonic Concorde and its Soviet copy, the Tu-144 (Knight 1976; Kelly 2005). The latter plane had a short, marginal career, and although the

small Concorde fleet kept flying for twenty-seven years (1976 to 2003, with a pause after the July 25, 2000, fatal accident on the runway in Paris), the plane lost money with every flight, a prime example of national (in this case, joint French-British) pride bought at a high cost for taxpayers.

Flying at the maximum speed of Mach 2.04 (about 2,160 km/h) while carrying just a hundred passengers was a formula for perpetual operating losses, an outcome that Boeing avoided by withdrawing from the supersonic race in 1971 when it abandoned its B2707, which was designed to fly at Mach 2.9. That plane was to be powered by four General Electric 4/JSP afterburning engines, while the Concorde used four 170-kN Rolls-Royce/Snecma Olympus 593 Mrk610 turbojets. The extremely high energy cost of the supersonic flight (at full power, the Concorde burned 10.5 t of fuel per hour), rather than availability of suitable engines, has been always the key problem, and this concern is even more acute in a new era of highly fluctuating oil prices and fears about imminent peak oil extraction. In addition, excessive noise and (a concern nonexistent during the 1960s, when Concorde was in development) an extravagant carbon footprint make any resurrection of supersonic flight highly unlikely.

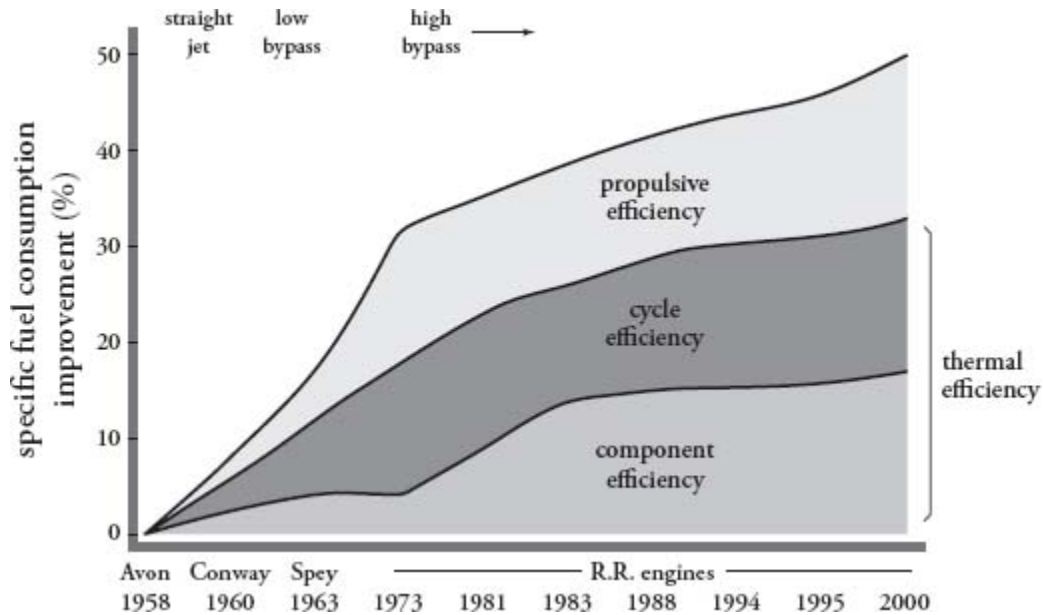
But speed always tempts, and the latest (rapidly aborted) attempt to go a meaningful bit beyond that half-century old subsonic limit was the conceptual design of Boeing's Sonic Cruiser, a plane that was to fly very close to the speed of sound at Mach 0.98 (that is, 1,040 km/h at the cruising altitude of 13.5 km), shaving an hour off the New York to Los Angeles flight for some 225 passengers (Wilson 2001). By flying higher and carrying fewer passengers than a standard wide-body jet, the Cruiser would have avoided the need for engines more powerful than those used by the Boeing 777 (eventually, the GE9-115B for its longest-range version), but it could make money only with much cheaper fuel (an unlikely possibility) or with considerably higher ticket prices. Initially, the Cruiser was seen as Boeing's unorthodox response to the Airbus A380, but the company shelved the project within months of its announcement in 2001 and decided instead to proceed with the Dreamliner (the Boeing 787).

The most likely prospect for the next twenty to twenty-five years (with Boeing having a massive backlog of 787 orders and with Airbus preoccupied with the A380 and a new A350 that is designed to compete with the 787) is that there will be no attempt to resurrect a supersonic passenger transport and to design a new jet engine specifically for this

purpose. Although constant improvements of existing designs must be expected, it is also reasonably safe to conclude that the maximum capacities of future commercial turbofans will not replicate the growth that those engines have experienced since the late 1980s. Today's largest turbofans (General Electric's GE90115B and Rolls-Royce's Trent 800) will continue to power, in twin or quad arrangements, the large fleets of different models of Boeings and Airbuses that will be in service for the next two decades. The only notable change in their composition over the next ten years will be the addition of scores of Boeing 787s (powered by General Electric's GENx and Rolls-Royce's Trent 1000) and Airbus A380 models (powered by the Trent 900 and Engine Alliance's GP7000).

Perhaps the most likely advances in engine designs are to be those that further improve their efficiency and hence reduce the environmental impacts of those powerful machines (National Research Council 2007; Williams 2007). Historical trends show that specific fuel consumption improved by 50 percent between the late 1950s and the year 2000, with most of the gain coming with the introduction of turbofans and due to a gain in thermal (component and cycle) efficiency (fig. 7.5). Average performance gain was less than 1 percent per year between 1980 and 2000, but Lee et al. (2001) expects specific fuel consumption to be down by another 15 to 25 percent by the year 2025 and energy per passenger kilometer to decline by 1.2 to 2.2 percent per year. Most of these future gains will come from incremental improvements due to better components and the enhanced efficiencies of existing designs, and it is unclear how much gain will be made by advances in innovative cycles of aircraft propulsion.

These proposals include the intercooler cycle, the wave rotors cycle, and the constant-volume combustor cycle (Corchero et al. 2008). The intercooler cycle uses a heat exchanger to cool the flow coming into the high-pressure compressor and transfer energy from the engine's core stream to the bypass stream. Wave rotors combine in a single device the functions that are now performed separately by a compressor and a turbine. The constant-volume combustor increases the cycle pressure and saves energy in the compression. As promising as these innovations may be, none will be ready soon for any commercial deployment, and all three will require solving a number of difficult technical challenges.



**Figure 7.5**

A long-term performance trend for Rolls Royce aeroengines (based on Ruffles 2000).

Substantial gains in greater environmental acceptability are expected, even without introducing any substantially new cycles. For example, the Advisory Council for Aeronautical Research in Europe (ACARE) has a number of challenging goals for engines to be introduced by 2020 compared to their predecessor (launched during the late 1980s). Nitrogen oxide emissions are to be reduced by 80 percent, carbon dioxide emissions by 15 to 20 percent, and external noise by 50 percent. Although it is not unrealistic to expect that these goals could be largely or fully met by 2020 to 2025, it is highly unlikely that the engines will be fueled by anything other than aviation kerosene. As in the case of diesels, concerns about the existing carbon footprint of gas turbines have brought proposals for future alternatives, with three very different options—synthetic jet fuels, biofuels, and hydrogen—getting most of the attention (Daggett et al. 2007).

Synjet fuel is produced from liquids made by the well-established Fischer-Tropsch process of hydrogenation of coal. South Africa's Sasol, the world's largest producer of coal-based liquids, has been supplying its isoparaffinic kerosene for blending with standard jet fuel (at a 50 to 50 ratio) to make a semisynthetic jet A-1 fuel that has been used since 1999 by all aircraft refueling at the Johannesburg airport. Based on this experience and on years of testing, on April 8, 2008, the British Ministry of Defense approved Sasol's completely synthetic jet fuel as jet A-1 fuel for

commercial use in all types of jet aircraft (Viljoen et al. 2008). Synjet does nothing to reduce the carbon footprint of aviation (it would actually increase it a bit), but it provides an alternative to petroleum-based kerosene. So does aviation biofuel (biojet fuel), which received media attention after Boeing announced in September 2007 that it will be testing such a liquid during short demonstrating flights of its 747 by Air New Zealand (Boeing 2007) and after world oil prices rose to nearly \$150 per barrel by July 2008.

The principal disadvantage of these fuels is their propensity to freeze at normal cruising temperatures (most plant oils have a freezing point just between 0 and  $-20^{\circ}\text{C}$  while jet A-1 fuel does not freeze until  $-47^{\circ}\text{C}$ ). Pure biojet fuel also has problems with thermal stability inside the engine. These technical problems could be overcome by blending and additives, but the key disadvantage of biojet fuels is (as with any phytomass-derived liquids) the extraordinarily low power density of their production (recall the examples of the ground areas that are needed for producing biodiesel). As a result, even when such fuels satisfy only a part of the overall demand, their production requires very large areas for the cultivation of seasonal or perennial oil crops.

For example, Daggett et al. (2007) calculated that if common American oil crops (corn, soybeans, and rapeseed) were to be used to supply just 15 percent of biofuel for a biojet and jet A-1 blend for the domestic aircraft fleet, the cultivated area would be approximately the size of Florida. Any significant production of biojet fuel would thus compete with the production of food and feed crops, and in the tropics (where it would be based on jatropha or on babassu palm), it would lead to further deforestation. The power density of biojet fuel produced from intensively cultivated algae would be considerably higher than that of today's generation of biofuels, and this has led to claims that the global fleet of jetliners could be powered by algal production harvested from an area the size of Belgium. Such claims, based on extrapolating from small bench-scale tests, ignore the very high energy demands of algal cultivation (particularly in closed bioreactors to avoid contamination by undesirable algal species in open ponds), which are needed to ensure the optimum temperature, mixing, exposure to sunlight, fertilization, harvesting, and drying of the algal phytomass.

I do not foresee biojet fuels as anything but an intriguing but impractical alternative, and I would argue that airlines could trim their carbon footprint

faster and without biojet fuel if they were to combine a number of organizational and technical advances that would prevent a significant share of wasteful fuel use. Towing airplanes to runways by efficient diesel-powered tow-trucks rather than making long taxi rides under their own power could reduce preflight fuel use (particularly in congested airports) by at least a third. Slowing down the speed of arriving aircraft to avoid or minimize wasteful circling in the vicinity of an airport is another simple and effective measure that could be optimized by integrating real-time traffic monitoring, weather forecasts, and flight-path designations.

Investigations of hydrogen as aviation fuel date back to World War II, the first engine tests took place in the United States in 1956, in 1988 the Soviets made short test flights with one of two Tu-154 engines powered by hydrogen-modified engines, and in the 1990s Germans set up Project Cryoplane in cooperation with the Russians (Contreras et al. 1997; Birkenstock 1998). Hydrogen's most obvious appeal is its high energy-to-mass density, which is about three times that of kerosene (120 MJ/kg 42.8 MJ/kg). Its other advantages are higher combustion efficiency (due to higher flame speed and combustion temperature) and hence the possibility of having smaller and less noisy engines.

But these advantages are negated by the fuel's very low energy-to-volume density (just a bit over 8 MJ/L of liquid hydrogen compared to about 34 MJ/L of aviation kerosene), by its extreme volatility, by a combustion that introduces much higher emissions of water into the upper troposphere, by the need for heavily insulated cryogenic storage (at  $-253^{\circ}\text{C}$ ), and by the impossibility of locating bulky hydrogen tanks in the wings (they must be placed beneath or above the passengers in the fuselage, thus increasing the plane's friction and passenger anxiety). A Russian proposal to solve the aerodynamic and safety challenges was to connect two air-crafts—a passenger plane and a liquid hydrogen tanker—with a flexible pipe that would be disconnected on the approach to the final destination and to fuel the descent and landing by relatively small on-board tanks (Struminskii et al. 1996). This may be seen as ingenious or as utterly impractical.

Even if the problems with hydrogen density, onboard storage, and flammability are satisfactorily resolved by technical advances, the capital investment in an entirely new supply and new airport infrastructures (pipelines, cryogenic tanks, pumps, safety systems) and the fuel's price will

ultimately determine its chances to become an alternative aviation fuel. Although powering modern societies by clean-burning hydrogen in safe and reliable converters (whether fuel cells or aeroengines) would be a welcome shift, hydrogen is not a primary energy source. It is merely a carrier of energy that must be produced by expending energy either from other fuels (made formerly by mostly hydrogenation of coal and now mostly by the steam reforming of methane) or by electrolysis of water. This means that the use of hydrogen can bring great environmental benefits (such as reduced carbon dioxide and sulfur oxide emissions) only if we get economically acceptable renewable modes of hydrogen production (such as water electrolysis by inexpensive photovoltaic electricity).

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During the millennia of their preindustrial evolution, humans' leading prime movers were their own muscles, and they later supplemented them with the muscles of working animals. Sails and water wheels were the only two inanimate prime movers introduced during the antiquity, and windmills came much later, at the beginning of the Middle Ages. The industrialization of the eighteenth century brought the steam engine, which was the first prime mover powered by combustion, and the amazing 1880s saw the introduction of gasoline-fueled internal-combustion engines (a prime mover that now has no rival in terms of total units in daily operation) and steam turbines (a prime mover that remains unsurpassed in its maximum unit power).

Despite the claims of accelerating innovation and the unprecedented achievements of technical progress in the twentieth century, only two new mechanical prime movers were introduced after 1890—Diesel's engine and the gas turbine. The first machine eventually claimed all but a tiny fraction of all of the shipborne cargo market and most of the land transport carried by trucks and trains. The second one is now the sole prime mover of long-distance passenger and freight flights. And these dominant positions have transformed the two prime movers into indispensable yet surprisingly ignored enablers of globalization.

Both of their inventors pursued their invention and their practical design with single-minded passion and devotion. It is no exaggeration to say that Diesel's life was eventually claimed by that experience and its deeply worrisome aftermath, and as Nahum (2004, 163) concludes, "Whittle was

almost consumed by the emotional effort of fighting for and developing the jet” and retired from the Royal Air Force at just forty-one years of age. Although their work has been subsequently altered, advanced, and transformed by an impressive march of scientific and industrial research and by engineering developments pursued by a multitude of experts in many disciplines in dozens of countries, the conceptual foundations and basic engineering outlines of the two great inventions remain intact.

By helping to transform the burdens of distance to a minor (in terms of cost and everyday practicality) commercial consideration and by making it possible to carry an ever-increasing mass of cargo among the continents and ever-growing numbers of people on international flights, the two engines have created a new spatial—and hence new economic, social and strategic—reality. This reality may not be completely global (in the strictest physical meaning of the adjective), but it has transformed economies that used to be deeply separated by oceans and connected only by relatively minor shipping volumes into closely related entities. Every minute, nearly a thousand containers are handled in terminals around the world, offloaded after intercontinental journeys, loaded with new merchandise, and moved inland or into storage. Every hour, oil terminals in Asia, Europe, Africa, Latin America, and Australia load about 200,000 t of crude oil to destinations on every continent. Every day, jetliners are boarded by more than 5 million passengers and loaded with more than 100,000 t of high-value cargo. Every year, shipborne commerce moves some 8 Gt of bulk and containerized cargo.

The magnitudes and intensities of these transactions changed the world as they abolished many long-established economic patterns, installed in their place new commercial realities, created new strategic dependencies and ensuing anxieties and fears, and contributed to the human degradation of the biosphere. An appraisal of the total impact of these two machines should go beyond cumulative quantifications of their performances, capacities, and deployments—all of which call for expressions of appreciation and for acknowledgments of remarkable progress—and also beyond their quantifiable impacts on resource uses, economics, and the environment.

The massive container ships that are powered by the world’s largest diesels and that bring Asian manufactures to America’s and Europe’s shores can be seen as ingenious enablers of previously unthinkable economic



globalization and as remarkable planet-spanning intermediaries that rationalize the use of resources, improve the standard of living in Asia's populous countries, and make consumer items more affordable for people everywhere. They can be also seen as the key links in a mindless chain of unsustainable economic growth that waste resources and pollute the environment to produce ephemeral goods even as they help to deprive the rich nations of most of their manufacturing jobs and turn them into societies driven by retail and financial services—a combination of dubious quality and inevitably brief duration. Can there be a common metric for these diverse (but often dubious) benefits and (often deeply upsetting) drawbacks so that we can arrive at the real, all-encompassing balance of the consequences?

Similarly, the wide-body jetliners that are powered by large gas turbines, the most reliable high-performance machines in history, have shrunk the travel time and made all but the earth's farthest circumpolar and the deepest desert reaches accessible in relative comfort and at a prices that can be afforded by hundreds of millions of passengers flying to make business deals, visit relatives or just experience different environments and cultures. But mass-scale long-distance flight is not only the best means of globalization on a profitable (albeit not invariably) scale or in a manner that enlarges individual horizons. It is also the means of erasing precious cultural differences (runways to accommodate wide-body jets are now on Bali as well as on Fiji, and the places opened to mass travel are all marked by that inevitable debris of modern tourism), propagating diseases, invasive species, and terror, and adding yet another human assault on the atmosphere. How can we value these disparate and some clearly unquantifiable losses and weigh them against the benefits of the shrunken world?

We simply do not have a suitable all-encompassing metric that we can use to weigh these multitudes of tangible advantages and gains and intangible losses and regrets to arrive at a satisfactory net valuation of the economic globalization energized by the two remarkable prime movers. I do not think I can do better than to recall Diesel's remark to his son Eugen which appears as the epigraph for this book's fifth chapter (Diesel 1937, 474):

It is wonderful to design and invent in the way that an artist designs and creates. But whether it all has a purpose, whether people have become happier as a result, that I can today no longer decide.

Surprisingly, it is possible to be more definite when thinking about the future of the two globalizing prime movers, simply because there are no comparably reliable and affordable alternatives ready to displace them either on the seas and roads or in the air. As far as we can confidently see, modern economies (whether they will be linked less closely than today or whether the globalization process makes a vigorous comeback) will continue to rely heavily on diesel engines and gas turbines. At the same, as shown so painfully by the greatest global recession in nearly eighty years, the particulars of economic situation, of everyday quality of life, and of political stability remain unpredictable, but these two judgments are easy to make. Whatever we have achieved in those terms since World War II has been due in a large part thanks to the advancing capacities and improving performances of those two prime movers. Whatever awaits us will be shaped in no small degree by their continued success, progress, or retreat.

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# Glossary

## Units

<b>bhp</b>	break horsepower (unit of power)
<b>dwt</b>	dead weight ton (unit of shipping mass)
<b>g</b>	gram (unit of mass)
<b>g/W</b>	grams per watt (power/mass ratio)
<b>GW</b>	gigawatt ( $10^9$ W)
<b>hp</b>	horsepower (unit of power = 745 W)
<b>km</b>	kilometer ( $10^3$ m; unit of length)
<b>km/h</b>	kilometers per hour (unit of speed)
<b>kN</b>	kilonewtons (unit of force)
<b>kPa</b>	kilopascal ( $10^3$ Pa)
<b>kW</b>	kilowatt ( $10^3$ W)
<b>L</b>	liter (unit of volume)
<b>lbf</b>	pound-force (unit of force)
<b>m</b>	meter (unit of length)
<b>MJ</b>	megajoule ( $10^6$ J)
<b>MJ/kg</b>	megajoules per kg (unit of gravimetric energy density)
<b>MJ/L</b>	megajoules per L (unit of volumetric energy density)
<b>mm</b>	millimeter
<b>MPa</b>	megapascal ( $10^6$ Pa)
<b>Mph</b>	miles per hour (unit of speed)
<b>m/s</b>	meter per second (unit of speed)
<b>MW</b>	megawatt ( $10^6$ W)
<b>Pa</b>	pascal (unit of pressure)
<b>rpm</b>	revolutions per minute
<b>t</b>	metric ton (tonne)
<b>W</b>	watt (unit of power)

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