
CSEP MODULE SERIES IN APPLIED ETHICS

This is one of a series of modules in applied ethics produced by the Center for the Study of Ethics in the Professions at the Illinois Institute of Technology under a grant from the Exxon Education Foundation. Each module consists primarily of an essay and contains illustrative examples and an annotated bibliography. The modules are intended for use in a wide range of undergraduate, graduate and continuing education programs in such areas as science, technology and human values, the sociology or history of science and/or technology, public policy and professional ethics courses in engineering, business and computer science. After a widely publicized call for proposals, authors and topics were chosen by a rigorous review process by the project's staff and Advisory Panel. Drafts of the modules were tested and evaluated by faculty and students in educational programs throughout the country. The final product, therefore, although primarily the work of its author(s), represents the contributions of many persons.

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Technology Assessment: A Historical Approach

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Introduction

Engineers have specialized knowledge and skills that are the bases of their professional status. The use of this knowledge has significantly affected the development of modern society, influencing the life and work of the community. Although engineering has its roots in antiquity the rapid acceleration of technological change since the eighteenth century has brought engineers new status and new responsibilities. The process of industrialization increased the demand for engineering skills and broadened the impact of the engineer's work. Increasingly, engineers have helped to shape modern society.

Many hold that the unique authority of their professional knowledge gives engineers special responsibilities. Society holds them responsible for the consequences of their work. The underlying ethical principle of engineering is service to the community. Modern codes of engineering ethics stress the primacy of public health and safety in the decisions of engineers.

One way in which engineers serve the community is by assessing new technology. Each technological advance, whether produced or implemented by engineers, has perceived benefits to society. At the same time, it may also have perceived (or unperceived) dangers which threaten the safety of the community. As scientific progress continually produces new risks (and uncovers previously unknown risks) the assessment of new technology plays an important part in bringing these risks under control. The term "technology assessment" has several meanings. In the narrow confines of this module it refers to the process of discovering the potential benefits and risks of new technology, weighing the social gains against the social costs, and then taking steps to influence the rate and direction of technological change.

Engineers have an important part to play in all three of these aspects of technology assessment. By virtue of their specialized knowledge and training, they are in the best position to estimate the risks of new technology. Engineers also have the capacity (far beyond the abilities of the average citizen) to evaluate the potential uses and abuses of a particular technology. Engineers therefore act in the public interest when they evaluate new technology. Engineers play a key role in the public debate about the social costs and benefits of new technology; they are in a position to initiate such debate, and expert testimony is frequently needed in the estimation of present and future risks, distribution of risks, and technological alternatives. Finally, engineers are often instrumental in increasing public sensitivity to technological change, a first step towards limiting risk by law and implementing public policy to manage risk, by means of informed discussion of the alternatives.

This module deals with the ethical decisions of two great engineers, James Watt and Thomas Edison. Watt introduced major innovations in steam power

and is recognized as the founder of mechanical engineering. Edison dominated the electrical industry in the nineteenth century and deserves to be regarded as the founder of electrical engineering. Both men introduced important new technologies, yet both opposed key innovations and attempted to hinder the development of still more advanced technology. Some scholars have explained their opposition to these innovations by the tendency of inventors to protect their own ideas. Others have suggested pecuniary and personal reasons. This module examines the actions of these two inventor-engineers in terms of their ethical concerns.

Watt and Edison created new technologies that offered increased efficiency. They both lived at times when, more than most other people, engineers believed that increased efficiency meant social and moral improvement, and the great engineering works of the eighteenth and nineteenth centuries testified to the scale and impact of their work. The economic and social benefits they brought made engineers leading members of industrial society. Men like Watt and Edison took pride in their increased professional competence and the far-reaching effects of their technologies. They had a naive optimism about the outcome of their work; they regarded themselves as architects of improvement and progress, and they foresaw great benefits from the forces that they had unleashed. Consequently, both assumed the role of guardians of the new technology. Public opinion associated them with the technologies they introduced, Watt with the steam engine, and Edison with electric lighting, and both felt a responsibility to the public for the efficiency and safety of the devices they introduced.

Although their concern for public welfare was motivated in part by financial advantage, altruism was also a factor. Each perceived that a dangerous technology would damage his reputation and the public image of the technology associated with him. Each correctly perceived that widespread fatalities would hurt his prospects of promoting a new technology on the basis of its superior performance and benefit to the public. Accidents and fatalities would also undermine the status of engineers. Both Watt and Edison tried to protect more than their own reputations and economic positions in their opposition to dangerous technologies. At stake was the position of engineers in industrial society and public confidence in them as agents of progress and well-being.

Through an examination of the controversy over nuclear power the last section of this module will show some of the unhappy consequences of a crisis of confidence of the type Watt and Edison feared.

James Watt and the Steam Engine

The steam engine symbolized both the process of industrialization and the progress of technology. The application of steam power to industry produced unprecedented increases in output and productivity. It transformed industry and was a central element in the factory system of production. In the words of the eminent economic historian, T. S. Ashton,

The new form of power and, no less, new transmitting mechanisms by which this was made to do work previously done by hand and muscle, were the pivot on which industry swung into the modern age (1948, p. 70).

The application of the steam engine to locomotives and ships produced even more revolutionary changes in transportation.

The development of steam technology involved continuous innovation and improvement. Some of the properties of steam had been known in antiquity, but no successful attempts to utilize it for practical purposes occurred before the end of the seventeenth century. In 1698 a military engineer, Thomas Savery, took out a patent for a steam pump that he called "The Miners' Friend." Savery's engine had numerous drawbacks, the most serious of which was a tendency to explode. At the beginning of the eighteenth century an English ironmonger (seller of hardware), Thomas Newcomen, impressed by the difficulties and expense of pumping water from coal mines, designed an engine expressly for that purpose. Newcomen's engine utilized atmospheric pressure to force a piston into the partial vacuum created by condensing steam in a cylinder; thus, strictly speaking, it was not a steam engine, but an atmospheric engine. Nevertheless, it enjoyed considerable success, and several hundred such engines were constructed in the eighteenth century, not only for pumping mines but also for raising water to supply cities and water mills.

The limitations of the Newcomen engine led other inventors to try to improve its performance. Several different lines of development were pursued with greater or less success, but the most important improvements took place in the eighteenth century, and resulted from the study and work of James Watt.

The life of James Watt illustrates the transition from skilled craftsman to professional engineer that occurred in the latter part of the eighteenth century. Born in Scotland in 1736, Watt received little formal education, but did obtain some training as a "mathematical instrument maker," or laboratory technician as he would be called today. It was in that capacity, in the University of Glasgow in 1764, that he first encountered steam technology in the form of a teaching model of a Newcomen engine which he was given to repair. Struck by the waste of alternately heating and cooling the cylinder by the injection

and condensation of steam, Watt invented the separate condenser, which he patented in 1769.

Despite the manifest superiority of Watt's improvement, he was plagued by both technical and financial difficulties until he formed a partnership with Matthew Boulton, a successful manufacturer of hardware in Birmingham, who in 1775 secured a renewal of his patent for twenty-five years. The engines built by the firm of Boulton and Watt achieved immediate success, especially in the tin mining industry of Cornwall, where coal was expensive. In the 1780s Watt obtained several more patents, including those for a double-acting engine (in which steam was applied to both sides of the piston), rotary motion, and a governor (the first automatic feedback or cybernetic device). Watt's improved engines were soon used in industries as diverse as flour milling, pottery, brewing, and distilling, not to mention the two most important users, cotton manufacture and ironworking. In the last two decades of the eighteenth century Watt's steam engine was the leading edge of technological change, not only in England and Scotland, but in continental Europe and America as well.

Watt's Opposition to High Pressure

The Boulton and Watt engines worked with low pressure steam, from 5 to 15 psi (pounds per square inch) above atmospheric pressure. This fact limited both their thermal efficiency and their economy. With higher pressures a smaller cylinder could have been used to generate the same amount of power. This would have permitted more powerful engines with a better power-to-weight ratio. Both steam locomotives and steamboats would have been technically impossible without high pressure engines. Watt knew the advantages of higher pressures—his original patent of 1769 envisaged the possibility of a high pressure, noncondensing engine—but he opposed their use, prohibited his assistants from experimenting with them, and used his patent monopoly to prevent competitors from employing them.

Some historians have accused Watt of opposing high pressure steam because of the commercial challenge to the firm of Boulton and Watt. One of his biographers attributed his opposition to his opinionated character, arguing that "excessive caution and sheer stubbornness led [Watt] to sustain his objections to high pressure steam long after they had been invalidated by technical progress" (Rolt 1962, p. 27). On the other hand, when Watt began his study of steam, engines were still novelties that harnessed a frightening new power. The engines of Savery and Newcomen were terrifying to onlookers; they belched flames, smoke, and steam, the result of inferior materials and poor fits of boiler plates and joints. Explosions were common. The new power was so "dangerous and unmanageable that it was doubtful whether it could be applied to any useful purpose" (Smiles, 1865b, p. 59). Although Watt was well aware of the theoretical advantages of high pressure engines, he also knew

of their dangers. He wrote, "I soon relinquished the idea of constructing an engine on this principle from being sensible it would be liable to some of the objections against Savery's engine, viz., the danger of bursting the boiler and the difficulty of making joints tight" (Rolt 1962, p. 27).

In addition to the problems of inferior materials, the first steam engine manufacturers had to contend with low standards of workmanship. Boulton and Watt did not begin as engine manufacturers; they were consulting engineers who supplied the blueprints and supervised the construction and erection of the engines. Their correspondence is full of their problems with quality control. Eighteenth century technology was not able to meet the high standards and close tolerances needed in steam engines. John Wilkinson, the ironmaster whose boring machine—originally patented for the production of cannons—enabled Boulton and Watt to produce their first successful engine, was the sole supplier of cylinders, "as there is no other proper apparatus in Britain for producing the parts with the truth and exactness we require" (Tann 1981, p. 8). The mechanics called upon to erect the early machines lacked proper training and skills; the ignorance and lack of skills on the part of machine builders and especially miners were frequently compounded with drunkenness. In the hands of "villanous bad workmen" (Boulton's words), the steam engine was a dangerous machine.

Although Boulton and Watt expected that their patent would ensure a monopoly of the new steam engines, they soon faced competition from other engine-makers, especially in the mining district of Cornwall. Injunctions were served on engineers infringing the 1775 patent, and among those restrained was Richard Trevithick. An engineer who had worked at several mines in Cornwall, Trevithick had also gained a reputation for his skill in erecting and operating steam engines. In 1795 he erected an engine designed by Edward Bull and it was for this infringement of the patent that Boulton and Watt served him with an injunction.

The steam engine patent of 1775 expired in 1800 and immediately many new designs of steam engines appeared on the market. Trevithick patented a high pressure steam engine in 1802. It dispensed with the separate condenser and expelled the steam directly into the atmosphere. It was both more powerful and more efficient than Watt's low pressure engines, and it had the added advantage of providing more power within a smaller compass, thus facilitating its use as a self-propelled power plant. Trevithick used his engines to power carriages and locomotives, and the subsequent development of steam-powered transportation owed a great deal to him.

Much has been made of the competition between Boulton and Watt and Trevithick; Watt's opposition to the high-pressure (which he called "dense") steam engine is often portrayed as pecuniary. The Trevithick engine achieved a rapid initial diffusion, for as early as 1803 his engines were being constructed at Coalbrookdale and other ironworks in England's industrial Midlands. Yet the Trevithick engine was only one of Boulton and Watt's competitors; even

John Wilkinson made pirated versions of Watt's design. In the words of Boulton, England had gone "steam mill mad," and the firm was hard pressed to meet the increasing demand for steam power. In 1800 Boulton and Watt's order books were full:

We are extending our manufactory of small engines but at this time the demand for them is far greater than our means for execution . . . we could not engage to execute any order of engines of this construction in less than 8-10 months"(Tann 1981, p. 17).

Watt based his public opposition to the Trevithick engine on its potential danger, although of course it also constituted a danger to his profits. The higher steam pressures increased the risk of explosion and in Watt's opinion this made the high pressure engine an unacceptable risk. Watt's assessment soon proved to be correct. One of the first Trevithick engines was used in a drainage scheme near Greenwich. In September 1803 it exploded and killed five workmen. The *London Times* (1803, p. 4) noted that this engine was operating at a pressure of 60 lbs. psi, compared with Watt's engines which rarely used above 7 lbs. psi. Watt felt vindicated.

The extreme danger attending the use of such an agent as dense steam has prevented us from attempting anything to do with it, and the recent explosion at Greenwich has justified our precaution (Tann 1981, p. 200).

As the technology of steam power advanced Watt found himself in an increasingly difficult dilemma: the trend toward greater efficiency and power also increased the risk of explosion. The technology that he had created escaped his control and became increasingly dangerous to life and property. Watt expected more accidents and deaths would result from adoption of high pressure steam. The threat to public safety now overshadowed the public utility of steam power.

Watt's training and early experiences as an engineer had fostered his belief that the new industrial technology could be a force for social and economic improvement. One of his first jobs as an engineer was to survey the route of the Caledonian Canal. This large engineering project linked two undeveloped areas of the Scottish Highlands and brought tangible social and economic benefits to a depressed region. Boulton and Watt believed that the steam engine could accomplish similar good works. According to its innovators the steam engine was not only a great step forward in engineering efficiency, "the most effective machine in nature," but also the vehicle of economic and social progress "by which the public will be the greatest gainers" (Smiles 1865b, p. 211).

Boulton and Watt took just pride in their competence, which was certainly greater than most in their profession. They had introduced a complex new technology, mastered it, and trained a generation of steam engineers. They also took pride in the efficacy of the engine; yet there lurks in their writings

a fear that here was a technology which could easily be corrupted and might prove a nuisance rather than a benefit. In a famous letter to Watt, Boulton argued, "We would serve all the world with engines of all sizes," and noted:

I presume that your engine would require money, very accurate workmanship, and extensive correspondence, to make it turn out to best advantage; and that the best means for keeping up the reputation, and doing the invention justice, would be to keep the executive part out of the hands of the multitude of empirical engineers . . . all which deficiencies would affect the reputation of the invention (Robinson and Musson 1969, p. 62).

What Boulton meant by "reputation" was the reputation of the technology itself as an agent for public well-being.

By 1803 signs that this reputation was becoming tarnished multiplied. But what could Boulton and Watt do? They were in no position to stem the economic forces that demanded more and more power from the steam engine. If they refused to develop the technology, many other engineers—most of them untrained and poorly skilled—were willing to take the risk of high pressure steam. What they could do was alert the public to dangers in the new technology and remind their fellow engineers of their special obligations to ensure public safety. Watt initiated the debate about the risks of the new technology and used his influence to press for safer, and better engineered, alternatives.

After the Greenwich explosion Watt began a publicity campaign to bring public attention to the dangers of high pressure steam. Trevithick complained:

I believe Mr. B & Watt is abt to do mee every engury in their power for the[y] have done their utmost to report the explosion both in newspapers and private letters very different from what it really is (Dickinson 1934, p. 60).

Watt succeeded in bringing the risk of high pressure steam into public view and provoking a debate about the acceptability of its risk. Writing in 1842, a German supporter of high pressure steam noted that the intense discussions of its defects and safety risks had clouded the issue of its advantages and had "disgusted the industrial community" (Alban 1848, p. vi). The author was convinced that the main barrier to the introduction of the new technology was the alleged danger of its use. He criticized English engineers for both building unsafe engines and for initiating the criticism of the dangers of high pressure steam.

Studies on the diffusion of high pressure steam technology have revealed that England lagged behind the United States and much of the continent in adopting these engines (Burke 1966). Von Tunzleman's study of steam power stressed the safety factors involved in the slow diffusion of high pressure steam in England (1978, pp. 80-90). The Greenwich explosion (and Watt's campaign against high pressure steam) came at a crucial stage in the introduction of Trevithick's engine, harming the reputation of both the engine and its builder and forcing Trevithick to incorporate safety features in his design.

By these precautions Mr. T. regained so much confidence as to obtain some orders for high pressure engines in London; but not as many as he would have received if the explosion at Woolwich [near Greenwich] had not deterred many persons from adopting his engine (Dickinson 1934, p. 61).

High Pressure Steam and Regulation

The risk from high pressure steam emanated from the boiler rather than from the engine itself; the majority of explosions were boiler explosions. The improvement of boilers lagged behind the rapid technological development of steam engines. Engineers quickly amassed scientific information about thermodynamics, the action of steam in the cylinder, the strength of materials in the engine, and many other aspects of steam engine operation. On the other hand, much of what happened in the boiler remained a mystery, and little was known about the buildup of steam pressure, the effect of corrosion and decay, and the causes of explosions. High pressure steam made many boiler designs obsolete and produced unmanageable strain on boilers; that was the fundamental cause of explosions.

The first steam boilers were little more than enlarged kettles or brewers' coppers. The early Savery engines used spherically shaped boilers which were made of copper and externally fired. The lower pressures used in the Watt engines gave Watt more flexibility in the design of his boiler, and he produced a boiler which was larger and had more heating areas than those which preceded it. The Boulton and Watt "wagon" boiler was often constructed of cast iron plates. This design achieved wide diffusion; it was economical in fuel consumption and easy to build and maintain. It was, however, unable to withstand the higher pressures of the Trevithick and Evans engines. As steam pressure in use rose from the 5 lbs. psi of Boulton and Watt engines to pressures up to 150 lbs. psi, new boiler designs were adopted. The success of George Stephenson's locomotives depended on his design of a multi-tubular boiler that could provide great amounts of high pressure steam. Stephenson boilers were far superior to his competitors', and made his locomotives economically and technologically feasible.

Engineers identified two major causes of boiler explosions in the early years of the nineteenth century: excessive steam pressure and weakness in the materials and construction of the boiler. Excessive steam pressure was the most obvious cause of explosion, and after several explosions in the first decades of the nineteenth century, safety valves were designed to eliminate this risk. Engineers believed that safety valves would reduce steam pressure when it reached a dangerous level, thus preventing an explosion. Another form of safety device introduced at this time was the fusible lead plug, which was supposed to melt when the temperature in the boiler grew too hot because of the overheating of the steam. These two safety devices were quickly introduced and were widely

used in locomotive, steamboat, and industrial boilers. Yet the number of explosions continued to increase. The much publicized technological "fix" of safety valves did not solve the problems attending the use of higher pressures in boilers.

Safety valves and lead plugs did not work because engineers did not fully understand what went on in steam boilers, and a better understanding of the dynamics of steam raising did not appear until well after mid-century. Engineers had also badly miscalculated the working environment of steam engines and the quality of attendants, the "human factor." Most designs for engines and safety features were based on the assumption that engine attendants would behave rationally and conscientiously. James Watt had already shown this assumption to be erroneous. The cause of the Greenwich explosion of 1803 was traced to the negligence of the engine minders, one of whom was a boy. Even the introduction of tamper-proof safety valves did not end problems of negligence. Engine drivers were normally paid on the basis of the number of trips completed. Consequently, in the case of locomotives and steam boats the attendants had an incentive to override safety valves.

The many statistical studies of boiler explosions carried out in England and the United States underlined the importance of the secondary causes of explosions—negligence and deterioration—which underlay the primary perceived causes of excess pressure and weakness of boilers. The greatest cause of explosions was usually found to be deterioration or corrosion of boilers, aggravated by negligence of the engine master and minder. It became evident that the human element determined the level of risk in steam engine operations, whether it was the wilful negligence of the engine master in using an old boiler that was incapable of sustaining high pressure, or the negligence of the engine minder in running the engine too hard. The answer to these problems was not found in a technological innovation but in a regular program of inspection and cleaning.

The early opponents of high pressure steam had suggested regulations to limit the uses of the new technology and thus, its dangers. This idea achieved little success; governments in the first half of the nineteenth century were not disposed to interfere with private enterprise. The steam engine embodied the idea of progress, and was part of the industrial technology that was responsible for "national progress almost unchecked, and of prosperity and happiness increased beyond all precedent" (Smiles 1865a, p. 517). The application of high pressure steam to transportation, which began around 1810, increased its uses and its supporters. The great benefits of railway and steamboat travel were extolled by the new engineering industry and the army of engineers involved in their operation. Engineers spoke for both sides in the debate about the acceptability of risk from high pressure engines. Many argued that the "moral" results of steam power—expressed in terms of the social and economic gains—were an acceptable trade-off for the risk involved.

Yet the ever present danger of explosion could not be ignored, especially in the light of the dramatic increase in accidents which followed wide-scale introduction of high pressure steam. The first large commercial application of the high pressure engine was on steamboats. The United States led in this area and by the 1820s and 1830s many engines were in use. Their use was marked by frequent and disastrous explosions. Passengers were blown up, scalded to death, hit by flying fragments of iron, and blown off steamers to drown in America's rivers and lakes [Howland 1840; also Burke 1966]. Industrial users of high pressure steam were also plagued by accidents.

An explosion of a steam-powered boat in England, following a series of industrial explosions, led to the creation of a Select Committee in 1817 to report on the dangers of high pressure steam. The committee began its report by acknowledging the great contributions made by steam power to national prosperity and by underlining the inexpediency of interfering with private business. Yet it noted that when public safety was endangered by "ignorance, avarice, or inattention . . . it becomes the duty of Parliament to interpose" (Parliament 1817, p. 223). The committee interviewed some of the leading engineers in the country, including Timothy Bramah and Henry Maudesley. It considered testimony by experts who believed that a risk was present in both low and high pressure steam engines. Taken as a whole, the evidence presented to the committee demonstrated the increased danger attending high pressure steam, and pointed to safety measures which would greatly decrease the risk. The committee's recommendations for frequent boiler inspection, however, were not put into effect.

Accidents continued at an alarming rate during the 1830s and 1840s. Trevithick's design was widely diffused in England at this time, both in locomotives and industrial plants. High pressure engines came into general use and existing steam engines were modified to work at higher pressure. Despite a steady improvement in efficiency the high pressure engine still constituted a danger to life and property. The increased use of steam power in transportation exposed more people to risk and the great loss of life prompted more government attempts to limit risk. In 1846 Parliament enacted a law to compensate families of passengers killed in accidents due to neglect or default (Parliament 1846). The United States had passed a similar law in 1838 which established the responsibility of owners of steamboats for accidents "occasioned by any derangement of the engine or machinery or any boat." The Act stated that any explosion aboard a steamboat "shall be taken as full prima facie evidence sufficient to charge a defendant . . . with negligence" (Howland 1840, p. 234).

These legislative attempts to limit risk failed to lessen the number of explosions. A Select Committee formed in 1870 to investigate steam boiler explosions found that there were about 50 explosions a year in England, which claimed on average from 75 to 100 lives. The committee called this situation "a national calamity," and noted that "explosions have come to be an established institution in this country, and a sad accompaniment to the use of steam"

(Parliament 1870, p. 579). By 1870 the high pressure engine was part of the fabric of industrial society. Yet, as James Watt had predicted, explosions were common and life-threatening; statistics gathered in 1870 showed that three times as many people were killed by boiler explosions as in railway accidents. These "frequent and fatal" accidents were blamed on the use of high pressures (Parliament 1870, p. 475).

In contrast to the committee of 1817, the committee of 1870 pressed for government involvement in the inspection process and the investigation of explosions. Its recommendations to Parliament anticipated a more active role for government in the prevention of explosions. The response of the British government to risk from explosions had changed, partly as a result of the increase in accidents, and partly because of the increased public sensitivity to the extent of the risk.

James Watt had been the first to bring the issue of risk from explosion to the attention of the public. Each subsequent explosion added weight to his argument that high pressure steam was unsafe. The increasing public frustration with the risk of boiler explosion can be seen in the hundreds of newspaper editorials on the subject. Boiler explosions even became a subject for literary treatment. Charles Dickens wrote satirically in *Household Words* (1851):

When a boiler bursts, why was it the very best of boilers; and why when somebody thinks the accident was not the boiler's fault it is likely to be the engineer's, is the engineer then morally certain to have been the steadiest and skillfullest of men?

The moralistic author, Thomas Peacock, blamed avarice in his novel *Gryll Grange* (1860):

Mrs. Opiman: You have omitted accidents, which occupy a large place in the newspaper. If the world grew ever so honest there would still be accidents.

Rev. Dr. Opiman: But honesty would materially diminish the number. High pressure steam boilers would not scatter death and destruction around them if the dishonesty of avarice did not tempt their employment, where the more costly low pressure engine would ensure absolute safety.

Peacock sided with James Watt in his emphasis on the social costs of high pressure engines, rather than with those who touted the economic benefits.

Most of the blame for explosions appears to have been placed on either the owner or the minder of the engine. Criticism was rarely levelled at the engineer who had designed the apparatus. But James Watt was an exception; he laid the blame for boiler explosions at the feet of the man who invented and introduced the high pressure steam engine. He is reputed to have said that Trevithick "deserved hanging for bringing into use the high pressure engine"

(Briggs 1982, p. 107). Watt's emphasis on the personal moral responsibilities of the engineer sprang from his appreciation of the enormous impact of engineering in a period of rapid industrialization. A handful of inventor-engineers, such as Watt, Fulton, the Stephensons and Trevithick, were creating the industrial technology that was changing the economy and landscape of the country. Their special expertise was greatly in demand because, in the early stages of industrialization, it was far in excess of the general understanding of the workings of steam power. The owners and minders of steam engines usually had little understanding of the workings of the engine and the limits of its operation. In the face of such ignorance, the "villanous bad workmen," and the overbearing concern for profit on the part of the owners (which Watt had soon noted in his dealings with the Cornish miners and others), the personal standards of the inventor-engineer were the chief element in the safe operation of the engine.

James Watt was aware of the increased influence and status of the engineer in an industrial society. The work of the early steam engine builders was quickly copied as the technology of steam power spread throughout the country. Watt and Trevithick not only produced the basic designs for generations of steam engines, they also trained a generation of steam engine minders and engineers. Their personal standards of safety and maintenance were therefore diffused along with the actual steam engines. Watt believed that the engineer had a personal responsibility to ensure a safe and efficient steam engine and bore culpability in case of accidents.

The economic advantages of high pressure steam overcame the opposition of Boulton and Watt and the fear of explosion. By the middle of the nineteenth century even die-hard opponents of high pressure engines, like the firm of Boulton and Watt, had begun to manufacture them. Yet Watt's original risk assessment had been correct: high pressure engines were dangerous. Watt had also been correct in his belief that new standards of precision and safety were essential in the design, manufacture, and operation of engines. When these high standards were finally enforced by government regulation in Britain in the latter part of the nineteenth century, the number of accidents fell dramatically.

The Boiler Explosions Act of 1882 in Great Britain established Boards of Enquiry into explosions and stiff penalties for negligence, but stopped short of inspection. This important work was carried out by the insurance companies, like the Vulcan Company, and private organizations, such as the Manchester Steam Users Association (Chaloner 1959). Frequent inspection, improved maintenance, and the diffusion of scientific knowledge about the action of steam in boilers combined to lessen the risk of boiler explosion. The statistics for boiler explosions in Britain show a steady decline from about 1875 onwards. In that year 50 recorded explosions killed 67 people. In 1905 only 14 deaths from boiler explosions occurred in Great Britain, compared with 383 in the United States. Inspired by the creed of rugged individualism

and a minimal role for the federal government, the United States had no program of boiler inspection on a national basis, and no agitation comparable with that of James Watt against boiler explosions. Although it had taken over a hundred years, and hundreds of explosions, James Watt's campaign against the dangers of high pressure steam engines had finally led to some success in bringing the risk under control in Great Britain.

Discussion Questions

Section One

1. Neither Boulton nor Watt anticipated the social consequences of the introduction of steam power. What role should be played by engineers in today's assessment of the social, economic, and environmental consequences of new technology, such as automation of the workplace?
2. Do engineers have a personal interest in promoting their company's good reputation for quality work and safe products? Does this reputation have a value in the market place?
3. How should blame be allocated when new technology causes accidents? To the owners, the designers (engineers), or to the agents on the spot? To all of them?

THOMAS EDISON AND ELECTRIC POWER

In the final quarter of the nineteenth century, when the high pressure steam engine had received wide acceptance both in Europe and America, a new form of power made its appearance. This was electricity, destined eventually to replace the steam engine as the principal source of inanimate power.

The serious study of electricity began in the eighteenth century, but it was not until the nineteenth century, with the discovery of the phenomenon of electro-magnetic induction by Michael Faraday in the 1820s, that the study had practical consequences. Faraday invented a primitive generator and electric motor, but no economically feasible means of generating power in large quantities was available until the 1870s. Low voltage applications of electricity were discovered in the new electroplating industry and in telegraphy from the 1840s, but one of the most obvious candidates for utilization of the new source of power was artificial illumination. Lighthouses began to utilize electric arc lamps in the late 1850s, and by the 1870s they were being used in a number of factories, stores, theatres, and public buildings. The practical shortcomings of arc lamps, in which an electric current jumped the gap between two open carbon filaments, thereby creating a flickering light, were serious; the most serious were the risk of fire and of electrocution. It was obvious that large pecuniary rewards awaited the inventor who could devise a safer method of electrical illumination.

At the same time, however, electric lighting would have to compete with two other recently perfected illuminants, coal gas and kerosene. Gas lighting began in the early nineteenth century, but became widespread only after the middle of the century. Lighting by kerosene lamps became possible only after the discovery of the first commercial petroleum deposit in Pennsylvania in 1859.

Thomas Edison, one of America's great inventive geniuses, hoped to reduce the danger of electric lighting by using low voltages for his incandescent lamps, which he patented in 1879, and which "subdivided" the light and enclosed its filament in a glass bulb. One enthusiastic press report, possibly inspired by Edison himself, hailed it as "a lamp that cannot leak and fill the house with vile odors or combustible vapors, that cannot explode and that does not need to be filled or trimmed." (New York *Herald* 1879). Edison planned a complete lighting system for general use, and intended it for mass adoption. He dreamed of electric lights in every home, and knew that public support would be essential. He therefore did his utmost to create confidence in the safety and reliability of his system. In 1882 he inaugurated the Pearl Street central station in New York, the first central electric lighting system in the world. This power

station supplied customers within a half mile radius with electricity to illuminate incandescent lamps. Edison had two priorities from the beginning in designing this system: it should be simple and it had to be safe. He admitted that his "heart was in his mouth" when the generators started up in Pearl Street (Martin 1922, p. 56).

Edison believed that the lighting system should offer no danger at any point. The propaganda campaign against electricity launched by the gas companies increased his sensitivity to the risks of electric lighting. The press soon made the public aware of the dangers of even this new form of electric lighting by publicizing accidents involving electricity. Insurance companies also noted the risks of electricity by adding premiums for electrically wired buildings. Edison fought a battle of public opinion to ensure acceptance of the new technology. His promotional material stressed the safety and reliability of his system.

Edison's Opposition to High Voltage Current

Edison's direct current lighting system was designed to serve customers within a short radius because distribution costs increased greatly with distance. As electric lighting became more popular, demand for electricity increased beyond the capabilities of the first central stations. The means to supply more people in large areas emerged from the rapid technological advance of the 1880s. Research on and development of alternating current technology provided the means to overcome the economic disadvantages of direct current. Alternating current could be transformed to high voltage and then economically transmitted over long distances. The high voltage lighting systems were built around very large power stations which took advantage of economies of scale. These systems could supply many more customers than Edison's direct current system, and their costs were normally less. By the late 1880s the new high voltage systems had achieved great commercial success.

Edison followed the development of alternating current with interest because the Edison companies had considered adopting the system when it was first invented in the early 1880s. Edison commissioned a survey of all research activities in this field, and he personally read the evaluations of the first alternating systems that were introduced in Europe. He firmly opposed the new technology and prevented the Edison companies from acquiring it (Edison 1889, p. 632).

Edison criticized the high voltage system on the grounds of its complexity, poor reliability, and threat to public safety. He believed that the potential damage that electricity could cause increased with the voltage. He thought that the high voltages used in alternating current systems would kill those coming into contact with it. This risk assessment was based on his detailed knowledge of electric lighting systems and his experience in designing and installing them.

Edison followed this unfavorable assessment of the risk of high voltage current with a vigorous campaign to alert the public to its danger. He made his views known in newspaper and magazine articles, and in speeches which were widely reported. He denounced the new technology as uneconomical as well as unsafe. Edison did not believe that the economies promised for alternating current could be achieved. His assessment found that the risk of high voltages could not be justified by the slight (or non-existent) economic advantages it offered. He evaluated the costs and benefits in both the economic and social dimensions of the new technology.

Edison initiated what was later called "The Battle of the Systems," which was waged between the supporters of two rival technologies. The chief antagonists in this battle were the large electrical engineering companies which had developed different lighting systems. Edison's chief competitors, Westinghouse and Thomson-Houston, both marketed high voltage systems. The debate began in professional meetings but soon spread into the public arena. The objective of each side was to convince engineers, legislators, and the general public of the superiority of its system. The electrical industry had no prior experience in this process because of the novelty of the technology.

The Edison interests took the matter directly to the public in a propaganda campaign designed to discredit the high voltage "death current." Edison's laboratory at West Orange, New Jersey, became the scene of public demonstrations pointing out that high voltage alternating current was fatal when administered to animals. The Edison interests then lobbied state governments to use high voltage electricity as a means of capital punishment. Harold P. Brown, a consulting engineer allied with Edison, succeeded in persuading the New York state legislature to employ electrocution for this purpose. The press vividly reported the grisly scenes of the early attempts at electrocution, thus heightening the public's fear of high voltage current.

The Edison interests followed the propaganda campaign against high voltage current with efforts to control its use through regulation. They urged legislatures to regulate the new technology in order to limit its risk to the public. The proposed legislation took several forms: it proscribed use of high voltages, it encumbered transmission systems with extensive safety features, and it outlawed alternating current in dwellings. All these conditions would have made it difficult, if not impossible, to operate a commercially successful high voltage system. The Edison interests were unsuccessful, however, and alternating current continued to be a strong competitor to direct current systems in the 1890s.

Why did Edison oppose high voltage alternating current? He was the leading advocate of electricity and the major figure in the campaign to win people over to the advantages of electric light and power. Many of his contemporaries in the electrical world thought his opposition was inconsistent with his earlier progressive ideas. The *Electrical Engineer* commented that "the most progressive man of his age cries halt to progress" (1889, p. 520). Many of his

biographers have stressed pecuniary motives in his stand against the new technology. The high voltage system was the leading commercial rival to the Edison system and overtook it in popularity in the early 1890s. Some historians have argued that since there was no economic argument against the new technology, "opponents of alternating current resorted to tactics outside the conventional realm of competition" (Passer 1953, p. 168), such as Edison's demonstrations with animals.

Two facts weigh against this argument. As Richard Schallenberg pointed out, Edison formulated his opposition to high voltages at the time of the Brush high voltage arc light, which was never a real threat to the incandescent light (Schallenberg 1983). If Edison had been motivated by purely pecuniary interests he would have taken one of several opportunities to acquire high voltage systems. At the time of the "Battle of the Systems" Edison had virtually divested himself of all his electrical interests, and spent most of his time experimenting in non-electrical areas.

Edison was a businessman as well as an inventor. There was certainly no lack of commercial consideration in his risk assessments. Yet his commercial outlook as a businessman was not in contrast to, nor a contradiction of, his engineer's pride in the competence of his work. He accepted the moral responsibility for the consequences of his engineering work as being an integral part of his activities as the leading entrepreneur of the electrical industry.

When it was first introduced, high voltage technology was a complex and experimental technology. Edison anticipated dire consequences from the introduction of alternating current systems:

Just as certain as death Westinghouse will kill a customer within six months after he puts in a system of any size. He has got a new thing and it will take a great deal of experimenting to get it working practically. It will never be free from danger (quoted in Josephson, 1961, p. 346).

Edison's assessment of the dangers of the new technology was partly based on his vision of a future electrically powered world. An important element of risk assessment of new technology is looking into the future to anticipate its long term consequences. As the champion of mass usage of electricity Edison foresaw a time when electricity would be distributed to every house and workplace in the country, and American cities would be covered by a web of electrical wires, some of them carrying high voltages. Edison recognized a "technological time-bomb" in high voltage current; its full danger would not be felt until some time in the future when it was in common use. He wrote:

With the increase of electric lighting (which today is used to only a very limited extent as compared with its inevitable use) and the multiplication of wires, these dangers which exist in a thousand different parts of the city will be manifolded many times (Edison 1889, p. 625).

His experience in installing and operating lighting systems had made Edison very sensitive to the problems of poor workmanship and ignorance on the part of the majority of electrical contractors. He was also concerned with the effect of wear and tear on electrical components. His own experience had shown that parts of the system deteriorated rapidly, increasing the risk of electric shock and fire.

The basic element in Edison's opposition to high voltage current was that the size and impact of the risk would increase over time. He knew that fires, deaths, and other accidents would mar the reputation of electricity and hinder its diffusion (Edison Archives). Edison had his own reputation at stake in the introduction of electricity. His name had become associated with high technology and practical engineering. This reputation, and the wide appeal of his name, was an important advantage in the marketing of the new technology. Edison and the companies named after him jealously guarded the reputation and use of the Edison name, signature, and picture. No other person was as closely associated with electricity in the public mind. Of course, Edison also had a commercial interest in preventing unsafe electrical systems from coming onto the market because he feared that accidents would reflect back on him and the companies that bore his name:

The Edison company, as proprietors of an absolutely safe system of domestic illumination, look with deep solicitude upon the possible advent of another system of lighting dependent upon the introduction of death wire into the inside of a dwelling or in contiguity therewith. The public will be slow in learning to discriminate between the different systems of electrical lighting (*Bulletin for Agents* 1883, pp. 21-22).

Edison was not the only inventor-entrepreneur to realize the commercial implications of unsafe technology. Elihu Thomson was a leading electrical engineer and one of the founders of the Thomson-Houston company. At first he opposed high voltage current as too dangerous. Yet rather than condemn the system and work for its elimination, Thomson attempted to find a technological solution to a technological problem. He believed that several safety devices would greatly reduce the risk of accident and continually pressed the business managers of the Thomson-Houston company to adopt such devices. Unlike Edison, Thomson was not the chief executive of the company that bore his name. Thomson was an employee—an electrical consultant and the head of research and development (Thomson Archives).

Elihu Thomson used all his power and influence within the company to convince management of the need to engineer a safe high voltage system. His arguments were based on the same desire for professional competence and good reputation that motivated Edison. He wrote to the chief executive of Thomson-Houston that the firm's "reputation will be that for completeness and safety" if proper consideration was made for avoiding risk of fire and shock.

He then pointed out the commercial advantages of this policy in the highly competitive market:

Wherever we have a plant that comes directly into competition with the Westinghouse people we should make it an example for completeness . . . [T]his would naturally bring a pressure on the Westinghouse people to provide similar [safety] devices, and being unprepared they would find it uphill work (Thomson Archives).

In the same memo Thomson recommended a propaganda campaign to bring attention to the dangers of the high voltage system that did not have safety devices. Thomson was proposing to the company a program of safety engineering which would have concrete results in the marketing of their products.

The Impact of Edison's Opposition to High Voltage Technology

Edison's great reputation as the nation's foremost electrical expert played an important part in the debate on the acceptable risk of the new technology. One newspaper reported that Edison "is probably the best informed man in America, regarding electrical currents and their destructive power" (*Albany Journal*, 1889). Edison realized that his fame was a useful tool in marketing his own products and in commercial competition with other electrical manufacturers, and as the previous section showed, his reputation was inextricably linked to all electrical products. The most influential of electrical engineers, Edison used his status and popular appeal to influence public opinion about electricity and its risks. His statements about the danger of high voltage technology were widely reported and brought public attention to the assessment of risk.

Edison directed his agitation against alternating current toward government. Like many electrical engineers of his time, Edison believed that government had a duty to protect the public from excessive risk. Even the supporters of high voltage current looked to government to provide the required standards of safety. Sebastian Ferranti, one of the leading alternating current engineers, wrote:

so we conclude that high tension [voltage] is as safe as low tension as long as it is carefully installed and run, low tension is unsafe . . . and will continue to be so until the state steps in and the use of electricity is regulated by well devised rules (Ferranti 1900, p. 43).

In contrast to Watt, Edison's opposition to the dangers of new technology was not directed at the engineers who designed it or installed it. His agitation against high voltage current was channeled towards the state. By the end of the nineteenth century engineers like Edison made a risk assessment and then

looked to government to protect the public from excessive risk. The threat of boiler explosions had brought government into regulation of private enterprise. As Burke has pointed out, boiler explosions produced legislation which showed a definite change of attitude on the part of the electorate and a new policy of positive involvement of government in the limitation of risk (Burke 1966).

Thomas Edison built on this process by suggesting that the risk from high voltage current be contained and regulated in the same way as risk from high pressure boilers. He argued:

When it became necessary for the protection . . . of the public to regulate boiler pressures in the city, the authorities proceeded on lines entirely different from those which are being followed . . . with electrical pressures; yet the cases are parallel, and the course . . . which resulted in a perfect system . . . should be retraced (Edison 1889, p. 628).

Edison wanted government to fix a limit on the voltages in use which would prohibit high voltages, and also provide a corps of inspectors to ensure the safety of electrical systems.

Although Edison failed to bring about a program of inspection and regulation of high voltages similar to boiler regulation, he did increase public perception of the dangers of high voltage currents. The first concrete legislation came soon after the "Battle of the Systems." This was directed at the overhead wire, which carried telegraph signals as well as electricity. These wires had been strung haphazardly in most urban areas and had been responsible for many accidents. Most of the leading electrical nations enacted legislation to control the erection and operation of overhead wires. Some cities banned them completely. This program was followed by several other attempts at regulating dangerous electrical technology as government began to recognize a responsibility to protect the public from risk.

In some countries government was quick to assume this responsibility. Great Britain passed an act in 1882 controlling all large electrical installations. Under the terms of this act the Board of Trade had the right to prepare and enforce "regulations securing the safety of the public" (*The Law Relating to Electric Lighting*, p. 65). On the other hand, the United States government was slow to become involved in electrical legislation and most of the regulation was done by individual states. Electrical engineers recognized that different levels of regulation produced different patterns of diffusion in Great Britain and the United States. Some British engineers believed that stricter regulation in Great Britain caused the alleged "lag" in electrical development (J.S.T.E.E. 1884, p. 409).

The extensive regulation of high voltage distribution in Great Britain was certainly a factor in the slow adoption of this technology, relative to the United States. Regulations setting out the minimum standard of insulation, for example, were stricter than was practically necessary and were blamed for the

high cost of installation. On the other hand, many engineers argued that the extensive regulation admittedly increased the cost but also lessened the danger of fire and injury. As a group, British electrical engineers in the 1890s believed that lack of regulation in the United States had helped the development of the electrical industry at the cost of more accidents, which were “so common as to be regarded as part and parcel of the system” (J.I.E.E. 1899, p. 470). In the same vein, British engineers condemned American laxity in the working and maintenance of steam boilers, which they believed to be extremely unsafe. The delicate balance between social costs and economic benefits was maintained at different levels on opposite sides of the Atlantic.

Edison and Watt both placed highest priority on the limitation of social costs in the introduction of new technology. They made their risk assessments, and took a stand against dangerous technology, because their positions as technological pioneers made them extremely conscious of the need for public and government support. There were two ways in which government could regard new technology: “as an infant that required nursing,” or as “a dangerous adult to be put into a straightjacket” (J.I.E.E. 1899, p. 470). Edison knew from experience that the latter course could severely handicap the introduction of a new technology. That is one reason why he insisted on a simple and safe system that could quickly achieve public and institutional acceptance.

Edison’s vantage point as chief architect of the electrical age gave him the same insights that had motivated Watt; both anticipated the need for higher standards of safety and precision in the engineering of new technological systems. Both began the process of involving fellow engineers, government, and the general public in raising professional standards and limiting risk. Edison and Watt used their reputations for professional competence to market their inventions. They believed that engineers had a responsibility to produce competent work, which included the utmost in safety. As engineering became a larger and more organized profession, professional societies took over this goal and began to set safety standards and attempt to enforce competent work. Yet whether it was the great engineer-inventor or the engineering society pressing for higher standards, the object was the same: the protection of public safety and with it, the preservation of engineers’ reputations and status.

In 1882 the Institution of Electrical Engineers (Great Britain) brought out a set of wiring rules aimed at raising the standards of design and installation of wiring. This action was prompted by the insurance companies who had increased the premiums on electrically-wired buildings. In supporting higher standards of safety the professional societies were also preserving their reputations because it was feared that untrained electricians and poor installation work would give the profession a bad name. Mindful that bad workmanship underlay the majority of accidents, and appreciating the need to ensure monopoly power, the I.E.E. rules stressed that “the chief element of safety is the employment of skilled and experienced engineers” (J.S.T.E.E. 1884, p. 409).

Discussion Questions

Section Two

1. Whose interests was Edison protecting when he opposed high voltage current—his own or those of the whole fraternity of electrical engineers?
2. Strict regulation can bring more safety but it can also slow down the diffusion of new technology. Who should decide on the relative importance of consumer safety versus the speed of diffusion?
3. What role should safety play in the marketing of modern technology? What role should government play in insuring public safety? Should it test all new products before use, as the FDA does for drugs, or wait until a risk is revealed?

Technology Assessment in a Contemporary Context: Nuclear Power

The use of nuclear energy to generate electricity provides a contemporary counterpart to the other two technologies discussed in this module. All three were advanced versions of new technologies, which offered revolutionary changes in the production and application of power. All three were the subject of unfavorable risk assessments which led to opposition. High pressure steam engines, high voltage lighting systems, and nuclear power were denounced as potentially dangerous new technologies which presented an unacceptable risk.

The major difference between nuclear power and the technologies of high pressure steam and high voltage electricity is the scale and complexity of the technological systems. Nuclear power is a prime example of the increased sophistication of modern engineering. The design and construction of a nuclear reactor is undertaken by teams of specialists each of which is responsible for one part of the plant's makeup. In the same way, risk assessment is now carried out by teams of engineers, rather than by one inventor-engineer. Yet the problems unearthed by risk assessments of nuclear power are similar to the problems of high pressure steam and high voltage electricity. So are the ethical decisions which engineers must make.

The first use of nuclear power was for the destruction of two Japanese cities in 1945. After this demonstration of the awesome power of nuclear fission ended the Second World War, attempts to transfer this power to peaceful uses began. The most promising use of nuclear energy appeared to be in the production of electricity. Such was the massive release of energy in nuclear fission that many engineers and scientists believed that this power could produce electricity "too cheap to meter" (Ford 1982, p. 210).

The first successful application of nuclear fission to the production of usable power was the U.S. Navy's program to build a submarine power plant. This was the work of Captain Hyman G. Rickover, who brought the program to a dramatic conclusion with the launching of the submarine "Nautilus" in 1954. The Navy's submarine reactors showed that it was possible to obtain usable energy from nuclear fission, and their successful operation spurred development of nuclear power stations. The first designs for power station reactors were basically larger-scale copies of the reactor systems used in submarines. When these were built in the 1950s it was discovered that the electricity they produced was not as cheap as first expected. Rather than being too cheap to meter, it was more expensive than electricity produced in coal or oil-fired power stations.

This situation paralleled that of the early days of electricity when Thomas Edison's direct current systems could not produce electricity cheap enough to compete with gas. In both cases the engineering answer to an economic problem

was the same: great increases in the size of the system produced economies of a scale which lowered the price of electricity. The average total output of the nuclear power plants built in the 1950s was around 150 megawatts. During the 1960s and 1970s the average output rose to 1000 megawatts. The rapid increase in scale in nuclear fission technology also brought unwelcome results. The complexity of the system increased and so did the magnitude of the risk. A 1000 megawatt nuclear power plant has the explosive potential of a thousand of the bombs dropped on Hiroshima and Nagasaki. The high pressure engine developed by Trevithick threatened the lives of its attendants. The engines and boilers used in steam boats risked the lives of hundreds of passengers. Thomas Edison feared that high voltage lighting systems would harm thousands of city dwellers. Befitting the technology of the twentieth century, nuclear power threatens the lives of millions of people. It even carries with it the risk of extinction of the human race.

The increased likelihood of risk did not deter scientists and engineers from developing nuclear power generators. The utility of an unlimited supply of cheap energy tended to outweigh considerations of its potential danger. One of the earliest supporters of the nuclear energy program was Edward Teller, a pioneer in nuclear physics and the "father" of the hydrogen bomb. Teller correctly anticipated that human error would always make nuclear fission a dangerous technology, but argued that "the unavoidable danger which will remain after all reasonable controls have been employed must not stand in the way of rapid development of nuclear power" (Ford 1982, p. 43).

The increased risk led to the development of design criteria for nuclear reactors intended to maximize safety. Reactors were designed to achieve "safety in depth," especially in the provision of a containment vessel which would prevent the radioactivity of the fission process from escaping into the atmosphere in case of an accident. In addition to safety features designed into reactors, the U.S. government set up a framework of regulation which was intended to protect public safety. The Atomic Energy Commission (AEC), and later the Nuclear Regulatory Commission (NRC), were charged with monitoring the design and operation of nuclear power technology, establishing safety guidelines, and enforcing safe operation of nuclear reactors.

In spite of this safety-in-depth policy, a number of engineers challenged the claims of safety made by manufacturers, operators, and regulators of nuclear reactors. Their risk assessments differed from those accepted by the nuclear power industry and the regulatory bodies. They were a minority in their respective fields, yet they had the courage to publicize their unfavorable risk assessments and press for changes in engineering and regulatory policy. The critics came from all sections of the industry. The problems they discerned in nuclear power technology were similar to ones which led James Watt and Thomas Edison to make their unfavorable risk assessments.

One thread binding Watt, Edison, and some of the atomic power engineers of the twentieth century was pride in professional competence. This motivated Carl Houston, a welding superintendent who worked on the construction of a

nuclear power plant. Houston found many examples of poor welding and inadequate quality assurance. He complained to his superiors and was told to be quiet or face dismissal. His subsequent dismissal for continued agitation only strengthened Houston's purpose, for he took his evidence to the AEC and later to the U.S. Senate (Houston 1978, pp. 264–68). Houston was part of a large force of engineers working on the project and his area of responsibility was small compared to other engineers. Yet he saw his responsibility for the quality of welding as an integral part of the overall responsibility for the safe operation of the reactor. He saw the possibility of great danger if the reactor were allowed to operate with less than first quality welds. He therefore took it upon himself to bring this threat to public attention.

Carl Houston's case is not an isolated example; the nuclear power industry has not compiled a good record for quality assurance, and there have been several cases similar to Houston's (Houston 1978; Faulkner 1981; Ford 1982). Examples of poor quality assurance made public by dissenting engineers range from incomprehensible blue prints to careless everyday maintenance. Both Watt and Edison realized that poor maintenance was a crucial element in the danger posed by new technology. Their experience in the field made them aware of the increased level of risk brought about by poor maintenance—even to supposedly fool-proof technology. Unfortunately, the full impact of poor maintenance in nuclear reactors was not appreciated until after accidents had occurred. The President's Commission on the Accident at Three Mile Island noted that many of the pieces of equipment that were centrally involved in the accident "had a poor maintenance history without adequate corrective action" (1979, p. 47).

Some engineers employed in the regulatory agencies spoke out about the inability of the regulators to enforce quality control and the reluctance of the manufacturers and operators to ensure it. The regulations themselves were not as stringent as those bearing on steam boilers and domestic electrical appliances. The regulations governing the components of nuclear reactors were modelled on the American Society of Mechanical Engineers codes developed for steam boilers in 1911, but without the important requirement for the third party evaluation and product testing. Critics of the regulation of nuclear reactors have repeatedly pointed out that the Nuclear Regulatory Commission has been unable to enforce even the basic elements of quality assurance (*New York Times* 1985, p. 26).

Many of these critics have come from the ranks of the regulators. Several high ranking engineers have resigned from the NRC because of its failure to limit risk from nuclear reactors. In 1976 a safety analyst resigned from the NRC because he believed that it was not fulfilling its mandate to protect the safety of the public. In his letter of resignation, Ronald Fluegge wrote:

NRC has covered up and brushed aside nuclear safety problems of far-reaching significance. We are allowing dozens of large nuclear plants to operate in populated areas despite known safety deficiencies that could result in very damaging accidents (Faulkner 1977, pp. 184–85).

The critics of the AEC and NRC stressed the regulators' commitment to advance the nuclear industry, and argued that the desire to promote the use of nuclear energy often outweighed the mandate to regulate it. The regulators of nuclear energy failed to ensure quality control, avoided challenging basic safety problems inherent in the design of reactors, and did not disseminate vital information about reactor problems. These three weaknesses were underlined in the post-mortem of the accident at Three Mile Island. The report of the President's Commission on the accident concluded that the NRC was unable to provide an acceptable level of safety in nuclear power plants and recommended a complete reorganization of the agency (1979, pp. 56, 61).

The deficiencies of regulation in promoting safety increase the individual engineer's responsibility for competent work and safe operation. These deficiencies also mean that the systems which are designed to prevent or control accidents become more important. The section on high pressure steam pointed out that technological solutions were quickly found for the problems of boiler explosions. It also noted that safety features did not always solve the problems. Safety valves and the like were based on an incomplete knowledge of the phenomena and did not prevent accidents. This same criticism holds true for nuclear power technology.

The design of safety features is based on risk assessments which attempt to anticipate the range of potential accidents. Critics of reactor designs found a much greater range of risk than the official assessments. Reactor designers paid most attention to the fuel assemblies in the reactor core and the primary heat-conducting loop around it. They anticipated that this was the major area of risk and then tried to imagine the worst possible single accident that could occur. They then designed systems to deal with potential accidents. One of the main classes of accidents studied was the Loss Of Coolant Accident (LOCA) where a leak in the primary loop discharges water and the core becomes uncovered, damaging the fuel rods and releasing radioactive energy. The technological solution to this problem was the Emergency Core Cooling System (ECCS), which floods the core and prevents it from melting.

Engineers critical of the regulations anticipated that the chief danger would come from a combination of small malfunctions rather than from one large LOCA. They further disputed the ability of the ECCS to prevent a core melt down. The ECCS was one of many safety systems which was not fully tested before implementation—a result of the economic imperative to hasten the construction of nuclear reactors and keep costs down. The AEC commissioned a team of engineers under the direction of David Rittenhouse to examine the events which would follow a LOCA. When they investigated the full extent of LOCA damage they found that previous understanding of the reactions was incorrect and that the ECCS would not prevent a core meltdown (Ford 1982, p. 97).

Critics of the safety of nuclear power plants realized that equipment designers only anticipated the obvious risks and failed to assess the risk coming from a combination of factors, including design faults, series of related malfunctions, and human error. Critics of the regulatory agencies alleged that the industry and its regulators only concerned themselves with risks that could be readily addressed, avoiding questions of basic design faults which were labelled "generic" problems with all nuclear plants and then ignored (President's Commission 1979, p. 51).

The evidence produced by a series of reactor accidents in the 1970s supports the critics of plant safety systems. There has been, up to the time of writing, no large LOCA in an American reactor. On the other hand, there have been several small scale LOCAs that combined with other malfunctions to produce major accidents. One element which seems to be present in most of the reactor accidents of the 1970s and 1980s is operator error. This was the basic finding of the President's Commission to enquire into the Three Mile Island accident. A small LOCA in the reactor went undetected, and subsequently the automatic ECCS cycle was manually turned off by the operators. This turned a small accident into a very serious situation which came very close to a core meltdown (President's Commission 1979, pp. 27-30). A similar accident occurred at the Salem Point reactor in New Jersey in 1983.

The engineers who operate nuclear reactors have few of the characteristics of the "villanous bad workmen" noted by Matthew Boulton. Yet they have less than adequate knowledge of the technology they tend and have made errors which, combined with malfunctions and basic design flaws, have led to accidents. It is significant that the largest reactor accidents have all been ascribed to human error: core meltdown at Chalk River reactor, Canada, 1952; core overheating at Windscale reactor, England, 1957; fire at Browns Ferry reactor, Alabama, 1975; and near meltdown at Three Mile Island in 1979.

The history of reactor operation has shown that the range and impact of human error is much greater than was anticipated by the early risk assessments of nuclear power. The likelihood of human error is a major difference between risk assessments made by those who support and those critical of nuclear power technology. The importance of human error in creating or increasing risk was first appreciated by Watt and Edison. Their fears were realized in the technologies developed from their inventions. The use of nuclear power illustrates how hard it is to design fool-proof systems which can compensate for human error. Even Edward Teller, a staunch advocate of nuclear power, admitted that

with the greater number of simians monkeying around with things they do not completely understand, sooner or later a fool will prove even greater than the proof in a fool-proof system (Teller 1960, p. 806).

The possibility of a completely fool-proof technology is a matter of engineering speculation. In the case of nuclear energy, it appears that little effort was made to design a fool-proof reactor. Critics of the basic design of reactors have charged that safety considerations came second to the economic imperative of producing competitively priced electricity. The nuclear power industry experienced a period of rapid growth during the 1960s. The slow building program of the 1950s was transformed into a boom beginning with the Oyster Creek reactor in 1963. Twenty-six new reactors were purchased by utilities in 1965 and 1966, and by the mid 1970s 170 new reactors had been ordered. They were based on new designs for very large reactors. The designs were sold and constructed before adequate testing and evaluation could be carried out.

As these reactors were completed and brought on line, unfavorable risk assessments made by concerned engineers increased. Criticism of the timing and nature of the technology in use grew within the nuclear power industry. To one engineer the rush to market an untried and untested reactor design was a breach of engineering ethics because these defects could easily lead to a disastrous accident. In 1974, when Peter Faulkner became convinced that these "engineering deficiencies" would not be made good, he resigned. (Faulkner 1981, p. 45). In February 1976 the nuclear industry was shaken by the resignation of three leading engineers employed in the General Electric Nuclear Division. Dale Bridenbaugh, Richard Hubbard, and Gregory Minor had all come to the same conclusion:

The industry, with the concurrence of the NRC, has overemphasized the theoretical approach in design verification with insufficient prototype, laboratory, or field test verification. The result is inadequate and unsafe design (Faulkner 1977, p. 315).

These engineers echoed Thomas Edison's opposition to high voltage current. Nuclear energy was still in an experimental phase and the technology being introduced was basically unsound and unsafe. Just like Edison and Watt, these engineers believed that an accident was inevitable.

The certainty of accident motivated these three engineers to oppose nuclear power technology publicly. In their letters of resignation, they argued that it was immoral to continue working on a project that presented an enormous risk. Bridenbaugh commented that "nuclear power is a technological monster that threatens all future generations" (Barnett et al. 1983, p. 247). All three had undergone a profound change in their attitudes regarding their engineering work. When they joined the industry they enjoyed a "missionary zeal" expecting that they would help develop a limitless source of cheap energy. Hubbard remembered:

We all got into the nuclear field because we thought we could do something good for mankind. . . . We had always thought of ourselves as the good guys who were providing the solutions. Suddenly we were the ones creating the problems (Barnett et al. 1983, p. 250).

These engineers closely associated the public good with their engineering work. This sentiment was shared by engineers who resigned from the regulatory agencies because of the latter's inability to protect the public interest. Robert Pollard resigned from the NRC in 1976 because, as he put it,

I could no longer, in conscience, participate in a process which so effectively evades the single legislative mandate given to the NRC—protection of the public health and safety (Faulkner 1977, p. 315).

These engineers, like Carl Houston and Ronald Fluegge, immediately made their risk assessments public. They recognized their responsibility to warn the public of the impending danger. The General Electric engineers stated, "We resigned our jobs to commit ourselves totally to the education of the public on all aspects and dangers of nuclear power" (Faulkner 1977, p. 281). Pollard thought that the American public was being misled into believing that nuclear energy offered solutions without risk. He was one of several engineers who defected from the nuclear power industry and joined the opponents of nuclear power. He used his expertise and influence to try to shape the development of nuclear power technology. Some dissenting engineers hoped that their efforts would bring an end to nuclear power. Others, like Fluegge, intended their opposition to act as a force to make beneficial changes in the technology. He wrote,

I intend to speak out, not as an opponent of nuclear power, but as a proponent of a useful energy source who wishes to see its serious safety defects promptly corrected (Faulkner 1977, p. 185).

The engineers who opposed nuclear power played a large part in increasing the public's sensitivity to its risk. Their actions also alerted government officials to the higher level of risk. Yet it is not evident that their opposition to nuclear power has had a major impact on the course of nuclear engineering or its regulation. Engineers like Fluegge, Faulkner, and the "G. E. Three" were termed "whistleblowers"—employees who forfeited their jobs to bring public attention to safety problems ignored by their employers. In contrast to Watt and Edison, engineers in the twentieth century are more likely to be employees of large corporations than independent inventor-engineers. This has limited their scope of action, but not their competence or moral obligation to make risk assessments of dangerous new technology. The opponents of nuclear power had neither the status nor the high visibility of Watt and Edison. Their warnings were, for the most part, ignored, and their motivation in opposing nuclear power was questioned. Although engineers like Faulkner raised basic issues concerning the morality of nuclear engineering, his interrogators questioned him on his hostility toward his employer rather than on the ethical responsibilities of engineers. His response to this line of questioning is significant: "I replied that this was a simple case of citizen duty transcending personal or

employee commitments." (Faulkner 1981, p. 481). Faulkner made no mention of any special responsibility of a professional engineer, and it appears that the professional engineering societies did little to support the whistleblowers.

It took a serious accident to give credibility to the risk assessments of the whistleblowers. The accident at Three Mile Island proved that many of the claims of the whistleblowers were well founded and the notion of a safe nuclear technology was brought into question. The result of the accident at Three Mile Island was increased public opposition to nuclear power and more stringent regulation. Several state legislatures began programs to eliminate nuclear power technology completely from their states. The President's Commission on Three Mile Island correctly identified the causes of this crisis in public confidence and accurately predicted its consequences:

We are convinced that, unless portions of the industry and its regulatory agencies undergo fundamental changes, they will over time totally destroy public confidence and, hence, *they* will be responsible for elimination of nuclear power as a viable source of energy (1979, p. 25, emphasis added).

Public apprehension about the risk of accidents was one factor in the increased vigilance of the nuclear power regulators in the wake of Three Mile Island. Although they did not address the basic "generic" design problems of nuclear reactors, they did increase their insistence on quality control and their attention to the risk arising from deterioration of plant facilities. In much the same way that corrosion and deterioration increased the danger of boiler explosions, deterioration of the plant increases the chance of a reactor accident and can be an important part in the chain of malfunctions that leads to an accident. In 1983 the NRC indicated that it considered these risks to be serious and closed down several reactors.

The nuclear power industry has been in depression for much of the 1980s. Many of the orders for plants placed in the 1960s and 1970s have been cancelled. No new nuclear reactors have been ordered since 1979. The future of nuclear energy looks bleak. California, Connecticut, Maine, Maryland, Oregon, and Massachusetts have enacted legislation which bans any further construction of nuclear power plants. Although the federal government is still committed to the development of nuclear power, "the promotion of nuclear power is not," in the words of Supreme Court Justice Byron White "to be accomplished at all costs" (*New York Times*, 1983, p. A24).

The crisis in public confidence which followed Three Mile Island also damaged the reputations of engineers because they were seen as responsible. By comparison with Watt and Edison most engineers in the nuclear power industry were negligent: not merely for allowing poor design and omitting safety controls, but also for failing to call attention to a dangerous technology. Engineers like Watt and Edison assumed a responsibility to make risk assessments and then warn the public if its safety was threatened. Many of today's

engineers have abdicated this responsibility, leaving it to managers and regulators. As Peter Faulkner explained,

It began to appear that I was working with people who had long since accepted their roles as narrow specialists. . . . The general feeling was that the industry eventually would solve most of these problems and that line engineers should leave complex management and policy problems to executives and experts (Faulkner 1981, p. 42).

The tragedy of the nuclear power industry was that, notwithstanding the critics mentioned above, engineers by and large left moral responsibility to managers and executives who had neither the motivation nor the competence to ensure public safety. The whistleblowers were correct in most of their risk assessments. The later history of nuclear reactors proved them right in critical areas such as the design of reactors, the effect of poor maintenance, and fallibility of human managers and operators. One important lesson to emerge from the Three Mile Island accident is that engineers were in the best position to perceive engineering and safety problems.

Watt and Edison feared that a major accident would seriously hamper the diffusion of new technology. This has happened in the American nuclear power industry. Watt and Edison were fearful of a crisis in public confidence in engineers and modern industrial engineering which would damage their reputations and livelihoods. This too has happened, for the crisis of the American nuclear power industry has hurt the livelihoods of many engineers. In an atmosphere of increased public perception of the dangers of new technology, the status and reputation of engineers seems to have diminished. Attacks on the reputation of engineers have followed this crisis of confidence. Roy Hattersley, a former British cabinet minister, wrote recently that:

The mystique of the professions has to be challenged . . . the professions appear less special. And the barbed wire around their protected lives is pulled away. . . .

The idea that the professions are linked by a common ethos is all part of the mumbo-jumbo of the middle classes (*The Sunday Times*, 1984, p. 14).

One way in which the engineering profession can enhance its standing is to perform its special responsibility to inform the public concerning the dangers as well as the benefits of new technology. Although technologies and the situation of engineers' employment have changed since the time of Watt and Edison, the responsibilities remain the same. As Watt and Edison correctly perceived, an unsafe technology would harm its own reputation and the reputations of engineers associated with it, to the detriment of all.

Discussion Questions

Section Three

1. Why were the economic benefits of nuclear power over-estimated? What could be done to prevent this kind of exaggeration in the future?
2. Is government regulation sufficient to guard the public interest? What is the responsibility of engineers in the process of regulation? Is it greater than the responsibilities of ordinary citizens?
3. How can historical analyses, such as those of steam and electricity, contribute to our understanding of contemporary technology development? What can those concerned with nuclear power learn from past experience with steam and electricity?

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