High Technology on Earth
Studies in Using Aerospace Systems and Methods

Paul A. Hanle
EDITOR
ABSTRACT

Hanle, Paul A., editor. High Technology on Earth: Studies in Using Aerospace Systems and Methods. Smithsonian Studies in Air and Space, number 3, 58 pages, 1 figure, 1979.—This collection of case studies describes how engineers or managers applied their arts to five complex problems on earth. A variety of aerospace methods and hardware were employed. Two of the cases concern "hard" technological developments: the construction of liquefied natural gas tankers and the creation of an automated system to transport people in Morgantown, West Virginia, both investigated by Susan Frutkin. Three cases address aerospace software and methods of analysis: the use of a technique of prediction developed by defense consultants, called "Delphi," by which opinions are collected and a sort of consensus is induced, investigated by J. Gordon Milliken; the use of mathematical modeling in a computer to simulate the flow of financial securities; and an attempt to reform some of California's public services through aerospace systems analysis, both investigated by Carole R. Cristiano. The focal point of each study lies in analyzing the political, technical, and bureaucratic forces at work in developing a complex system. Each study is summarized in a separate, short comment, which also discusses how conflicts of goals and judgment conditioned the outcome of the development. The editor's critical introduction to the entire work places the five studies in a context of contemporary writing on technology and society.
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A few words are in order to explain what is attempted in this book. We should begin with a disclaimer: it is not a litany of benefits from the aerospace industry, nor is it a study of the impact of "technology transfer" as the National Aeronautics and Space Administration (NASA) and other federal agencies have fostered it. Rather, this small collection of case studies describes how engineers applied aerospace arts to five complex problems on earth, each of which entailed dealing with an array of hazards and in which were employed a variety of aerospace approaches. The cases range from the development of liquefied natural gas tankers to the reform of some of California's public services. In addition, they include the construction of a "people mover" in Morgantown, West Virginia; the use of mathematical modeling to simulate the flow of securities; and the use of a technique called "Delphi" for collecting expert opinions and inducing a sort of consensus. To be truthful, none of these studies document the history of problems that have been completely "solved," although there were several impressive technical successes.

The focal point of each study lay in analyzing the forces at play in developing a complex system, not merely in pronouncing each attempt a success or a failure. To accomplish this analysis would mean to learn a little of how to use other high technological inventions, and this was the purpose of our research. We have concluded that it is always difficult but still productive to attempt judiciously to use aerospace inventions for other purposes. Not only what is judicious, but how that is determined is the crux of each of the cases presented below.

The following studies describe managerial methods as well as technological "hardware," the approach of systems analysis, and the discipline and principles of aerospace engineering. Encompassing the processes of using these, a suitably general but definite term was sought to motivate the title of this book, for each of the usual terms was in some way unsuitable. To scholars of international economic and technological development, the familiar but ambiguous "technology transfer" means international aid: sending bulldozers to Iran and teaching villagers in Upper Volta to drill deep water wells. "Fringe benefits of space" and "spin-off" are associated with NASA, but much of the technology described below comes as well from work done on federal defense contracts, a circumstance that occurs again in a larger sample of cases than presented here. (The reason is that the source of much invention resides in the aerospace contractor, who has both NASA and defense work, not in the contracting agency, which may wish to take the credit.) "Technology utilization," though homely, comes closest to describing the situation. Unfortunately, in normal aerospace usage it also embraces the profitable use in flying machines of aerospace technology—the technical benefits of the "Landsat" Earth Resources Satellite, for example—and these are excluded from this book.

So we have settled on a less elegant phrase—using on earth the technology of the air and space industry, or simply aerospace technology on earth. There is no difficulty in denoting the diverse elements of aerospace expertise with the term "technology," because technology has in recent years come to mean the application in general of knowledge for practical ends, and that application may be through discipline, principle, methods, hardware, or people.

Such concern for a proper title may seem gratui-
tous. Still, if one does not begin on the right foot, one soon stumbles in this obstacle-strewn field. Like the distinction between industrial invention (creating an original thought or device) and industrial innovation (changing that which is produced for sale or use, the distinction between building air and space vehicles and applying the expertise gained thereby is crucial, yet it is often muddled in lay and professional minds alike. Furthermore, it is both transfer and diffusion of technique that we consider here, a broader sweep than is properly covered by the terms we have discounted.

**Research for the National Air and Space Museum**

In early 1972, the administration of the National Air and Space Museum began to plan a permanent exhibition on the "Benefits from Flight." As one of the major exhibitions of the Smithsonian Institution, "Benefits" received congressional funding of one-half million dollars and required four years to complete. The exhibition opened with the new museum on 1 July 1976. Two and one-half of those years had been devoted to research, documenting instances of the use of aerospace technology on earth. From the hundreds of case studies that were pursued initially by researchers working in the museum, a number of which were researched subsequently by hired experts, the editor selected the five studies this book comprises. After the cases were chosen, authors Frutkin, Miliken, and Cristiano researched them additionally to take account of events through September 1975; they then rewrote them to conform to the narrative format.

The question remains as to why such an intense program of research was undertaken in the first place. We can answer only by reviewing how the "Benefits" gallery was conceived. A proposal of 1973 to Congress for funding this exhibition and research suggested ambitiously that "... 'Benefits from Flight' can serve as a powerful and productive channel for this sorely needed technology transfer process." As the curatorial staff (which included two principal investigators before the editor) delved into the literature, they found increasing need to document thoroughly the cases of benefit to mankind that were to be presented in the gallery. It was not enough to list the "dividends" of aeronautical and space research in the sort of roll that administrators of federal agencies, probably to their distaste, found necessary each year to recite. For the purpose of a major exhibition, which would bear the Smithsonian imprimatur, be visited by five million or more persons each year, and ideally foster more innovation, narrative stories had to be founded on research of a depth and style theretofore not undertaken.

If this was not obvious at first, it became so after the hired investigations got underway. Many instances of applying aerospace technology had not been researched fully, and each of the cases investigated by the researchers seemed to be governed by its own set of rules. Soon they concluded that the scope of the term "technology transfer" was too limited—it was not a process, but many processes, each of which seemed to be defined only by the case that it described. These processes were entwined on each other so that they became harder to follow the further one progressed from the starting point. Indeed, there seemed to be a principle of frustration at work, in which if one began with a "benefit" (a device, system, or even an idea of immediate use), its connections to aerospace industry were lost in a mist of subsequent commercial development; or if one began with the aerospace invention, its application on earth appeared to sink into a pool of further invention and modification. It was nearly impossible in either case to trace the thread of "transfer," because, as the researchers finally accepted, no single thread existed.

One well-known social commentator recognized this fact several decades ago. In his innovative study of 1946, *The Social Effects of Aviation*, William F. Ogburn spoke of the reasons for the difficulty of tracing derivative effects of inventions, reasons that our investigators found to be valid in many of the cases they studied.

We have noted that these derivative influences do not operate alone, but join with other influences, and that the derivative influence of any one invention seems to thin out and lose force. Furthermore, these derivative influences fan out in various directions. It therefore becomes rather difficult to isolate, trace out, and measure the derivative influences of an invention.

"But," concluded Ogburn, "these influences are real and produce social changes, despite the fact that they are difficult to measure." While the existence of derivative effects was not in question, either by Ogburn or by the museum's researchers, the latter came to Ogburn's conclusion and had to settle for a description of the facts of the cases as they could find them, eschewing as much bias as possible. Even this little information, the researchers and the editor hoped, would hold some lessons for how people innovate with aerospace technology on earth. The cases exhibited in the gallery and the five cases presented below were studied partially to this end.
The Reasons for Selecting These Five Studies

From a field of 21 unpublished, contracted researches, the editor wished to choose a sample of studies of reasonable length, which would represent the highest quality and the most interesting relationships of humans to technology while reflecting the diversity of the entire research program. As it happened, the criterion of quality was applied with greater rigor, and thus the distribution of studies has been skewed toward certain topics: transportation systems, management, systems analysis, and prediction. Although medicine, public service, energy, computer analysis, and other topics also were investigated (and were treated in the exhibition), the majority of this research is not presented here. Quality and broad interest have been represented at the cost of heterogeneity.

Though obliged to state this, we feel no need to apologize. In the following studies, circumstances and events appear that are as representative of all attempts to use aerospace technology as those that have not been published. Indeed, if the purpose of this collection were only to aid specialists in each industry represented, there would be little reason to bind them together in one volume.

But we can make more stringent claims on this collection and so answer the question of why one might want to read them together—that is, why we have chosen to compile this anthology at all. In short, the cases were chosen for their illustration of general principles, not for their speciality. For example, while Susan Frutkin’s story of the Morgantown “people mover” reveals some of the workings of the Boeing Company, it more importantly portrays the need to perpetually reconcile social and technological interests in massive government programs. The development of liquid natural gas tankers points to a common, perhaps the most important, method of industries reusing aerospace technology—the physical transfer of persons. Gordon Milliken’s study of Delphi methods suggests the uses and limitations of some techniques of industrial planning that have been borrowed from air and space industries. Carole Cristiano’s studies of simulating the flow of financial securities on a computer and of simulating four urban services of California hold similar lessons: the problems of systems of society may be too complex to model yet or, worse, they may be impossible in principle to reduce to computer analysis. The editor has joined the authors in hoping that these five instances may be understood in their details, but beyond this that they may provide a body of evidence to support a general view of more universal interest, a full-systemic approach, to which we now turn.

A Hidden Presumption in Much of the Literature of “Technology Utilization”

In an unpublished draft of comments on using aerospace technology, Louis L. Bucciarelli, the National Air and Space Museum’s former curator of science and technology, has questioned a recurring presumption in the literature of technology that we too shall wish to examine. It is that the development of new technology, like the machine, runs by itself, independently of the human spirit. He observes:

Those concerned with the maintenance of a viable economy assay the accomplishment of technological innovation and dispersion. “Technology Transfer” and “Utilization” are their key words. These persons see “barriers” to the dispersion of technique: talk in terms of time lags—duration from invention to widespread use—and recommend policies to shorten this period. They trace out in hindsight a sequence of related events, improvements in technique, and scientific discovery that have converged on a new hybrid corn, a heart pacemaker, a solid state component.

Behind this endeavor is the unstated presumption of technology as “thing in itself.” Technology as “black box”—a self-contained unit that one builds, plugs in, and reaps the benefits of. Technology as something out there to be discovered and developed to meet human needs upon demand. Technology as having an independent existence like the law of universal gravitation, as some perceive it.

To suggest that technology be considered as a cultural artifact, like art, literature or music is to view the matter from a quite different, more fruitful perspective. Who would attempt to transfer our most popular literature to a less developed country for its self-improvement?

Following Bucciarelli, we invite the reader to examine the connection of technology to the rest of human endeavor in the five case studies that follow. We acknowledge from the start that they suffer also from a deficiency of humanity, but what they indicate is more than has appeared before.

Bucciarelli criticizes a view that has been expressed often in the years since the mid-1960s. As electronic automation and control played an ever more prominent role in society, Lewis Mumford and Jacques Ellul projected the image of technology out of human control. They legitimized it to a great extent, even if, as Langdon Winner has shown, it had its historical and literary precedents. Universities created programs of “Technology and Society” in part to investigate their charges. In sociology, politics, history, and philosophy, scholars began to explore the manifold relations of humans to their technological and material culture. Now the products of their research are beginning to reinforce the view that we must understand technolog-
ical development as part of a larger structure of human social and political development. These scholars have, in their holism, surpassed the critiques of Mumford and Ellul. We shall return shortly to who they are and what they have to say.

Why must man and technology be understood in their interaction, rather than as independently functioning components, and how does this apprehension pose problems that programs of technology utilization do not address? It is because valuation of technology is a key ingredient, because it is a measure of technological success, the link between mankind and technology, and yet the element of analysis that advocates of "utilization" pay little attention to. If we insist that the goal of federal technical programs, or example, is to create the best quality of living for the most people, then we may indeed find that these programs move us toward the goal with purely technological or economic successes, ends that those who seek "utilization" pursue. The values are firmly established, if unstated. Sometimes we find, however, that the welfare of society is best served by renouncing these narrower forms of "success" when they threaten goals or needs that we rank higher on a scale of value. Thus nuclear breeder reactors have not been developed as fast as was once expected, partly because of growing fear that they are unsafe, first among environmentalists but increasingly among others who stand to be endangered (and benefitted) by them. Many people of reasonable mein now agree that the danger outweighs our need for more electric power—from this source at least. So also, the aeronautics and space energy sponsored an expensive, impractical "sight switch" to direct a motorized wheelchair, and after the device had proved its technical feasibility in prototype, its manufacturers ceased production, because they could not make it work under "real" conditions. NASA promoted the device, it is fair to say, beyond the point where reasonable expectations of practical return had withered, and it died in a jungle of competing values. Neither NASA nor the energy agencies considered these values, for they were not thought to be part of the "technical" problems the agencies were created to handle.

Are these examples of failure of technology or of failure of people? From these failures, wherever we place them, can we draw lessons for the future use of aerospace technology? Author Robert Pirsig has suggested one answer to these questions, which we find most interesting and in close alliance with the views of Ida Hoos, whom we quoted above, and several others. Pirsig has put forth his view in the form of a perceptive story titled *Zen and the Art of Motorcycle Maintenance*. He has much to say, we think, to promoters of aerospace technology. Pirsig explains that the way to understanding how we value technology lies in our analyzing the relationship of humans to technology and not in bestowing absolute traits on either one. Regarding what many see as ugliness in technology, he asserts:

But the real ugliness of modern technology isn't found in any material or shape or act or product. These are just the objects in which the low Quality appears to reside. It's our habit of assigning Quality to subjects or objects that gives this impression.

The real ugliness is not the result of any objects of technology. Nor is it, if one follows Phaedrus' metaphysics, the result of any subjects of technology, the people who produce it or the people who use it. Quality or its absence doesn't reside in either the subject or the object. The real ugliness lies in the relationship between the people who produce the technology and the things they produce, which results in a similar relationship between the people who use the technology and the things they use.

Much modern technology—the trashy plastic utensils and the "lemons" of the assembly line—bears the onus of "low Quality," not because that quality resides in the things themselves, but because it is reflected in the often mean, uninspired manner in which they are conceived and used. We must evaluate technology in the relationship between the object and its user. This relationship reflects that between object and maker, and to "value" technology is to judge that relationship to be good.

To those who maintain that what Pirsig calls the relationship of subject and object rests solely in the technology itself or in the persons who use it, microbiologist Rene Dubos, allied with Pirsig on this point, offers a genetic metaphor. Dubos writes of "important problems of life," though his musing is evidently intended to exceed the bounds of biological science:

Present scientific fashions notwithstanding, there is no valid reason for believing that the most important problems of life concern its analysis in terms of genes, their subunits, or the chemical reactions they control. Far more important, it might be argued, are the complex interrelationships between living things and their total environments. Civilizations are generated by such interrelationships. Life is so profoundly influenced by the evolutionary, experiential, and social past that even a highly sophisticated physico-chemical approach leaves out of consideration most of its determinants and manifestations. "We murder to dissect," Wordsworth said in "The Tables Turned."

Since the living experience disappears when the organism is taken apart, many aspects of human life can be understood only by studying man's functioning with all its complexities and in the responses that he makes to significant stimuli. Such a study would require an organismic and ecologic attitude very different from the analytic one which now prevails in biology.
The wisdom is age-old. Dubos notes that the Hindu mystics who composed the treatises called the "Upanishads" pointed to such an organismic attitude 2500 years ago. It applies as well to mankind's use of technology.

We have cited Mumford as one who projected the image of the soulless machine of technology; now we must again take care to distinguish between his attitude and those of Pirsig and Dubos. Mumford would place the source of human alienation from technology in the "systematic dissociation [of work with machines] from the rest of life." He views the development of power-harnessing machines as a curse, and so his attitude epitomizes that of a group often identified as "anti-technologists." He believes that mankind's technological burden has accrued to it because it has allowed technology to dominate. Mankind (the race) and technology (the object) are alienated from each other, but this is a consequence of something intrinsic in the technology itself. Pirsig and Dubos, however, condemn less the machines than those who would blame some intrinsic evil for their domination of our lives. Dubos raises a call to "make technology subservient to worthwhile human needs," and this sounds, as one recent critic has observed, like a reaction against Mumford's self-determined machines. In Dubos's view, however, holism bears emphasis, for only in the whole of man and environment is carried the basis by which we value technology, the element of human relationship to technology in production and use. So better we might ally Dubos and Pirsig, and we think that their views are substantiated in the cases that follow.

Let us conjure one last writer, the recent critic Samuel Florman. A successful engineer and a reasoning technocrat, Florman has described some of the rewards and frustrations of building and using machines. His analysis of the views of the antitechnologists proceeds from their writings, and he concludes that their collective viewpoint resembles that of Jacques Ellul. "A primary characteristic of the antitechnologists is the way in which they refer to 'technology' as a thing, or at least a force, as if it had an existence of its own." His and Bucciarelli's criticisms are similar, though he addresses the antitechnologists; Bucciarelli comments on the promoters of technology transfer. If the two are to be identified, as the quotation suggests, we leave the unsavory task to the reader.

Unfortunately, Florman has linked Dubos's poetic imagery closely to Mumford's and Ellul's more pessimistic expressions. But on balance Florman has summarized adequately a major element of the movement, and he has attempted to show where it has gone awry:

But sober thought reveals that technology is not an independent force, much less a thing, but merely one of the types of activities in which people engage. Furthermore, it is an activity in which people engage because they choose to do so. The choice may sometimes be foolish or unconsidered. The choice may be forced upon some members of society by others. But this is very different from the concept of technology itself misleading or enslaving the populace.

He summons philosopher Daniel Callahan to deny the dualism of man and technology and to replace it with a view of technology as but one of the manifestations of man:

At the very outset we have to do away with a false and misleading dualism, one which abstracts man on the one hand and technology on the other, as if the two were quite separate kinds of realities. I believe that there is no dualism inherent here. Man is by nature a technological animal; to be human is to be technology. If I am correct in that judgment, then there is no room for a dualism at all. Instead, we should recognize that when we speak of technology, this is another way of speaking about man himself in one of his manifestations.

On this point, finally, it is the conclusion of writers like Pirsig, Dubos, Florman, and Bucciarelli that earlier critics of "technology" have erred in choosing their objects of criticism. Even the masterful Lewis Mumford and Jacques Ellul have tended to elevate "hardware" above mankind's acts of creation and use of these tools. Instead, we must look more closely at the relationship of mankind and technology. When we examine this relationship, we look for the values within it. Our conclusion is not so important as the process of studying the relationship—of finding the values—because in that process we identify social forces arising from these values, which play against each other and determine the direction of our technological society. Such a study, which is hardly begun in the cases that follow, may hold lessons for the future of aerospace technology. We think that our approach, at least, is how those writers whom we have cited might deal with our problems. Our goal is to understand those social forces. If the studies fall short of the mark, it is because our effort has been insufficient, not because the method is wrong.

Finding the Values

How might one evaluate explicitly the relationships of people to technology? We have already noted that elements other than the economic are involved when we look at each case. (We emphasize this because to a large extent, it seems, economics motivate people to
Technical elegance alone may bring the relationship to flower. In the history of science there are few clearer instances of a researcher fashioning a symbiotic relationship with his experimental apparatus than that of physicist A. A. Michelson. In almost five decades of research around the turn of the century, he nursed the instruments he invented, coaxing from them both precision and high reliability. In his duplication of Foucault’s measurement of the speed of light, then later in his much-repeated interferometric determination of the constancy of the speed of light (propagating perpendicular or parallel to motion of the source and detector), the legendary precision of Michelson’s experiments was unequaled. When his scientific successor Dayton Miller later attempted the same experiment with a much larger interferometer at the top of Mount Wilson, his conflicting results caused some concern, but physicists finally discounted them. According to visiting theoretical physicist Max Born at least, the source of Miller’s error was to be found in the unreliability of his elephantine machine. In the terms used above, we can say that Miller failed to evolve the quality of the relationship between him and his experimental apparatus that characterizedMichelson’s research.

Another element of technological value is shared with science. It is that the maker and thence the user may feel a sense of joy in creating and manipulating the invention—in bringing it to function as it was intended. The feeling is that of sport or play, and it has been discussed by many scholars, most notable among them the psychohistorian Lewis Feuer. While some critics dispute his claim that the rise of modern science in the 17th century was due to “the spirit of play,” we note that he has identified an element of research that also motivates engineers. “Technical and scientific work is usually fun. In fact, creative technical work provides much the same satisfaction that is obtained from painting, writing, and composing or performing music,” affirms President Jerome Wiesner of the Massachusetts Institute of Technology. The engineer solves his technological puzzles as intently as others decipher cryptograms; he designs his machine as creatively as a composer writes a concerto. The value of a masterpiece accrues to him who rejoices in the act of creating it as much in engineering as in musical composition. And we, the users, if we are in a sympathetic frame of mind, value it also for the joy and skill of its creation. For some, there is the mere inspection of an antique airplane or automobile, a graphic print, or the structure of a bridge; for others, it is the bond of human and machine, the life-and-death dependence of a driver on his racer that brings joy and a keenness to his senses.

We may find that competition enters into the way we ascribe value. Does it seem that advocates of the United States supersonic transport placed much value in surpassing the Russians and the French-English consortium? The American project of the 1960s entailed not just building such a transport but making it the biggest and fastest of the lot, finally to the detriment of the entire project.

The element of control of purpose has come increasingly into debate in massive “high” technological developments, since the beginning of the recent era of heightened awareness. Too often, it seemed, interested individuals or groups usurped our right and obligation as users to measure the purpose to which our technology would be put. One need but recall the revelations of Ralph Nader, who in the mid-1960s examined the mechanical integrity of the Detroit automobile and declared it lacking. The industry, it appeared, had allowed the technology of safety to take a back seat to that of speed and mass production. To the automobile business the purpose of the car was profit, and it came at the cost of safety to passengers. As soon as this fact was widely known and accepted (it is no longer controversial, as major “recalls” are often corporate admissions of past mistakes), the value of the owner’s relationship to his automobile diminished. As if to rebuke Detroit, American consumers began to purchase neatly manufactured, though rarely safer, foreign models. The purpose of the builder-machine relationship had been altered since the days of the Model T, and with it the value that many had perceived in domestic cars.

Other elements of valuation may arise from peripheral sources. The secondary consequences of a person’s use of mechanical technique may alter his attitude toward it. (Consider the case of Theodore Taylor, whose preoccupation with the technical elegance of the atomic bombs he created yielded to his growing alarm that these devices could be home-built and used for terror and extortion.) The mere fact of success, especially in a complex undertaking, can excite the imagination. (Consider the Viking Mars Landers, which brought no sign of extraterrestrial life to earth by 1977, but which nonetheless caused a flurry of lectures, popular publications, and general interest among more than space enthusiasts.) And, of course, there are others.
Yet something lacks in such an analysis of the elements of valuing a technological relationship. Did we not aver that one must look at the relationship holistically and so not "murder to dissect"? In each case cited, indeed in each that can be found, the elements of value are determined by the greater culture of both creators and users of technology. For Michelson, the greater culture was unambiguously defined by those who shared the values of physical science. For the automobile industry, however, problems arose when the elements of valuation in the world of business diverged from those of the nation of users. The industry's disregard for certain values of the users (like passenger safety) engendered mischief.

A lesson from this and other cases (like the computer model of securities exchange discussed below, which proved less cogent than expected because its creators ignored conservatism and rivalries among the exchanges) is that we must not underestimate social aspects in a "technical" problem. Repeatedly, as we shall see, it is these social aspects and their political overtones—specifically the conflicts of value within the entire culture that creates and uses the technology—that precipitate the fall of a "technical" program. The balance sheet that betrays the failure is only one measure of it and does not reveal the underlying social forces that caused it.

And yet we find in the cases to be presented that the complexity of society often renders an "at once" analytical and unified view impossible. In four of the five cases, problems occurred as much because the social values were unidentifiable or undefined as because the developers made no effort to grasp them. Who could identify the cultural norms of 60 different agencies with which the builders of liquid natural gas tankers had to deal and each of which claimed to protect the interests of society? Who was to say finally of the purpose of a personal rapid-transit system in Morgantown, West Virginia, whether priority should be given to solve traffic problems of that university city or to demonstrate a prototype of similar systems to be built throughout the country? Who was to say if the securities exchange industry was modeled to protect, reform, or replace the existing industry? Could one possibly have considered all the conflicting values of those who supplied and used the California services that were analyzed? It seems sometimes that if such endeavors work at all, it is because those who are involved in them share an unstated will to succeed that overpowers their often strongly stated conflicts of other values.

The examples suggest, then, as Ida Hoos would argue, that we cannot solve fundamental social "problems" through a purely engineering approach. Holism is antithetical to analysis, and in any event the problems lie less in technique than in the conflicts of value of "builders" and "users." It is the irrational in us that sustains our values, and these values account for, indeed define, technological failure or success in society. Perhaps those who develop technology need more cultural vision, not more analysis, if they are to apply their (and our) machines successfully to social ends.

Our use of holism has its origins in organic metaphor, so we must underscore that we are likening the relations of people and machines to those of organisms. This admission is not to fully preclude the possibility of rational analysis. C. P. Snow, on the contrary, noted that holism "has nearly always been a trap for working scientists. DNA and the genetic code would never have been unraveled by people who were moved by the concept of holism." Instead, the research scientist works on his narrow problem, divorcing himself purposely from his surroundings so as to gain a "controlled environment" in which he can measure minor changes of the system he observes as he varies each parameter of that system. Where this separation perturbs only little the system being measured, the scientist (or technologist) is on firm turf. But the ground becomes soft when, as in many social "systems analyses," the exclusion of social, political, and other cultural influences cuts the heart out of his problem. The point is that we are all social beings, more or less, and a few are trained to reason as scientists or engineers. It is reasonable to call for the rare abilities of engineers who allow the living factors into their studies. If by so doing, the methods of engineering are weakened or rendered useless, then the analysis must pass to other techniques. Not all are analytical, indeed many are not even rational, but are proper elements of using aerospace technology on earth.
Notes

1. See, for example, Hymen Olken, Technology Transfer: How to Make It Work (Livermore: Olken Publications, 1972).


3. Major Exhibition Programs, Fiscal Year 1974, Smithsonian Institution (budgetary document).


5. One example: Public Technology, Incorporated, in preliminary research under a contract from NASA, tested a cold mix street-patching material which "found to be the best formulation after some of the early tests, appears to be demonstrating the kind of permanence and durability cities and counties require," (ibid., part 4, page 28), according to President Porter W. Homer of Public Technology, Incorporated. Yet, according to the subsequent study performed for the museum by PTI Vice President Warren D. Siemens, "the amount of improvement over the city winter mix of the . EVA-modified cold mix was not [significant]" (unpublished report).


7. Ida Hoos has expressed this view with respectability and vigor:

The engineer soon discovers that crime, welfare, and the like are not one system, but many systems: not one problem, but many problems, only some of which fall within any disciplinary or "scientific" scope. Indeed, for most social problems, there is no technical or methodical "solution." Their very definition depends on the point of view of the analyst; his value system is imbedded in the way he designates the objectives, identifies pertinent variables, and assigns costs and benefits. And in all these crucial matters, his schooling and experience as an engineer may hinder rather than help him. Thanks to the process of "trained incapacity," he, probably more than any other professional, purposefully rivets attention on certain types of problems or aspects of them and does well what he does, with careful disregard for those matters which he considers outside his purview. (Ida R. Hoos, "Systems Analysis as Technology Transfer," Journal of Dynamic Systems, Measurement, and Control (March 1974), pages 1-6, especially page 3.)


10. Philip Handler, president of the National Academy of Sciences, counsels caution: "Before such a program is implemented, it must be examined in the most intimate detail and the public must be satisfied that the risk to future generations is of an acceptable order; that the latter is the case is not self-evident at this time." Quoted from "On the State of Man," Interdisciplinary Science Review, volume 1 (September 1976), page 196.


17. Dubos, So Human, page 231.


19. Ibid., page 48.

20. Florman continues:

Making due allowance for poetic license, it is clear in these repeated personifications that technology is considered to have an existence separate and distinct from individual human beings. Indeed, technology is thought of as something that, unless fought against, can do things to human society, such things as "claim priority," "take over" and "dictate," even "ravish" and "murder." Dubos muses that although technology cannot theoretically escape from human control, society feels threatened by technological forces "just as it was threatened by the raiding Norsemen and Saracens ten centuries ago."

This way of thinking has spilled over into common usage, so we are not surprised to see an advertisement that begins, "Technology has trapped us . . .," or an article in a news magazine that says, "Technology is seen as a dangerous ally" (page 49).

21. Ibid., page 58.


23. See, for example, J. Schmookler, Invention and Economic Growth (Cambridge: Harvard, 1966). Schmookler's hypotheses have come under increasing criticism, but his ground-breaking statistical study remains cogent.


27. We make no claim that America's increased market for foreign cars was caused by Nadar et al., only that they contributed to the growing American affection for the imported car.


Politics and the People Mover

Susan Frutkin

EDITOR'S COMMENT

This study of the 11-year history of a personal rapid transit system, a "people mover," in Morgantown, West Virginia, is rife with technical data that bespeaks the author's care in research, but it also contains interesting analyses and judgments. Her story centers on the interaction of three factions responsible for building the people mover: the Congress of the United States, which appropriated more than $60 million for the test project; the administrators from the Department of Transportation, who distributed the funds and managed the entire program; and the engineering contractors and consultants, who planned and built the system. Author Frutkin investigates the politics of this interaction; and when one regards the billions of dollars that the federal government distributes each year in technological research, her political theme is of great importance.

Morgantown's problem in 1965, the frequent congestion of automobiles on the two main roads of the city, precipitated an alliance between the administration of West Virginia University and a member of the faculty, industrial engineer Samy Elias. Together they sought funding for a system to transport students across the city between campuses several miles apart. Elias knew that there had been no major changes in the technology of mass transportation in this country in 60 years, nor were the older technologies suited to the needs of Morgantown. He advocated developing a new system based on high technology.

For their part aerospace interests were involved for other reasons. The Boeing Company, uncertain of future defense contracts sought to diversify into mass-transit systems. At the same time, the Department of Transportation, which funded the project, sanctioned hiring the well-regarded Jet Propulsion Laboratory to manage design of the system. Further stimulus to aerospace participation in the project came in 1970 from the Urban Mass Transportation Act, which encouraged use of then economically depressed aerospace companies. The evidence presented leaves no doubt that aerospace industry built the Morgantown project because both government and the industry perceived that it could develop a new technical system rapidly.

The people mover at Morgantown was to be a demonstration of new mass-transit technology. In early grants to West Virginia University, the Department of Transportation had insisted that the system be developed with the intention of using the new techniques in other cities; but allowing even for its status as a prototype, the project had many problems. The preliminary phase of the program, which included operating vehicles on an elevated guideway, was rushed to completion before the 1972 national elections. A breakdown of one of the five vehicles during dedication ceremonies in October was described by one bureaucrat with a melancholy juxtaposition of metaphors: "It was ridiculous . . . like putting five breadboards in the field." Later extensive tests showed that components were defective, systems for safety and guidance were inadequate, and computer electronics contained errors in logic. Installation of the 45-car system was completed only in September 1975 with final costs more than quadruple the original, no doubt unrealistic, estimate. While many of the problems appeared to be technical in nature, they often stemmed from underestimation of the time as well as expense of developing a new system. Then too, the conflicting wishes of the university, the Department of Transportation, and Congress contributed to the feeling at the end of 1975 that none of the three factions would be happy with the system. Nevertheless, the Morgantown people mover is operating, and it carries people from one campus of the University to another in that small city. Furthermore, the federal government planned in early 1977 to fund at least three new people movers in larger cities. The Morgantown system holds the status of prototype of these systems.

Throughout the study, interviewees lamented that internal and congressional politics were allowed to interfere with technological development. Underlying their complaints is the manifestly vital issue that those who develop technological systems wish to free themselves of "political" restraints, to solve their problems in isolation from an untidy world that will not let them. Yet it is the untidy world that poses the problems in the first place. So engineers can only be lauded for bringing their problems into tractable dimensions, yet their analysis is no less incomplete for doing so to the exclusion of political concerns. A lesson of the people mover is that developers of technological systems for society must learn to "reckon" with political factors, indeed with many social factors that cannot be quantified, for the systems derive their reason for being from the benefit they provide a society where priorities are set in the first instance by political means.

Introduction

In the early 1960s, the town of Morgantown had a population of about 22,000 residents and as many West Virginia University students and staff. Morgantown runs along a river on steep hilly terrain; only two streets completely traverse it. The University has three main campuses: one downtown, the other two at opposite ends of town. While they are only 1.5 miles away from each other, by the early 1960s, traffic jams

Susan Frutkin, formerly with Booz Allen Applied Research, Bethesda, Maryland, now with American Petroleum Institute, Washington, D.C. 20037.
required 70-minute separations between classes on different campuses, and there were five periods of peak travel.

Dr. Samy Elias, who had earned a B.S. degree in aerospace engineering and M.S. and Ph.D. degrees in industrial engineering, joined WVU’s industrial engineering staff in 1965. For a number of years, he had taught and conducted research on computer applications to urban transportation. After experiencing Morgantown's traffic problems firsthand, Elias became interested in the idea of a research project for the engineering department to devise a new transportation system for the town. Over a two-year period, he brought together the university's president, an engineering staff, and an advisory committee of community leaders and planners to study Morgantown's chronic traffic problems.1

Proposal for a New Transit System

Based on discussions and study of alternatives, WVU and the advisory committee concluded that Morgantown needed an innovative transit system. They decided that the town's topography and population distribution precluded widening highways or building new ones. They also agreed that it was important to minimize operating costs (the largest component of which is labor) while providing maximum service. Any new system would therefore have to be either elevated or subterranean and would also have to rely heavily on computerized automation.

In 1967, WVU presented a proposal reflecting these decisions to the Department of Housing and Urban Development (HUD, the responsible agency at the time) for federal funds to study the feasibility of an innovative urban mass-transit system. The proposal contained several unique features. For the first time, it addressed the problem of a mass-transit system in a small city. In addition, the system was to operate 24 hours a day in response to different levels of demand. Furthermore, the proposal called for testing the system in an urban setting instead of at the usual remote test track.

Either because of the low priority placed on mass-transit research and development at the time or from sheer inertia, HUD did not act on the proposal for two years. In the interim, however, impetus to new initiatives in this area came from the 1966 Reuss-Tydings Amendment to the Urban Mass Transportation Act. The major objective of this legislation was to apply advanced technology to mass-transit problems, and it called for a program of research, development, and demonstration of transportation systems for metropolitan areas of various sizes. The law eventually helped generate interest within government and industry in the development of automated guideway transit (AGT) systems, among other new technologies.

In 1968, the environment for conducting research on and development of mass-transit systems was further improved by the support of the incoming administration. The Urban Mass Transit Administration (UMTA, created in 1964) was transferred to the recently created Department of Transportation (DOT). As Elias put it, “It was a new administration with a new language.”

In May 1969, Elias visited Secretary of Transportation John Volpe to request consideration of his long-pending proposal. Volpe liked the idea of testing small vehicles operating on demand in a community, especially one like Morgantown, where the problems were manifest and local initiative to solve them was evident. In July 1969, Volpe approved $100,000 for the study; WVU contributed $35,000.

In about a year, Elias had completed the feasibility study for a personal rapid transit (PRT) system, also called a “people-mover.” Using a “systems” approach, typical in aerospace work, he identified major subsystems and analyzed their interrelationships. He also studied construction and operating and maintenance costs, along with such mechanical factors as high speed, automation, and distances between cars.2 In all, Elias considered about 130 PRT concepts before selecting Alden, Varo, and Dashavayor (Bendix) to do preliminary studies, for which DOT-UMTA granted an additional $20,000.

After WVU staff and an outside consultant evaluated the preliminary engineering studies, they chose Alden, a small nonaerospace company with two computer-run prototype cars, to build a system featuring 6-second headways between cars.

During this period, the WVU staff considered two management approaches for design and construction of the system: The university could hire 30 to 40 engineers in addition to its regular staff, or it could hire a systems manager. Based on suggestions from various people involved during the initial studies, WVU contacted the aerospace-oriented Jet Propulsion Laboratory (JPL) and Bendix Aerospace Company about assuming the function of project manager. JPL was selected on the basis of cost and its nonprofit character, which was considered more appropriate for a program with the potential national application of PRT systems.3
In August 1970, WVU submitted its proposal to UMTA for a federal grant of $13.5 million to begin designing the PRT system. Alden's initial request had been for $25 million, but when UMTA said it could not commit the full amount to one project, WVU lowered its request to $13.5 million. Few who were involved actually took the $13.5 million figure seriously. Lack of staff, lack of understanding of what would be involved, and the desire to present the PRT as a cheap program were some of the factors that drove down initial estimates. Unfortunately, this approach was to backfire and its consequences would plague the entire project throughout its development.

By mid-1970, however, congressional pressure was increasing to apply advanced technology to national problems. The Urban Mass Transportation Assistance Act was passed, permitting DOT to provide capital grants to any community for rejuvenating old or creating new mass-transit systems, including PRT systems. The new law specifically encouraged use of depressed aerospace and defense industries to develop new systems. West Virginia's Representative Harley Staggers was also a strong and influential supporter of the Morgantown program.

UTMA, too, was now actively interested in conducting programs to demonstrate technical feasibility, public acceptance, and cost effectiveness of an advanced PRT. The agency considered Morgantown a good initial test site for acquiring demonstration data, on the basis of which DOT could begin certifying systems for capital grants.

**Approval for the PRT**

In September 1979, UMTA granted $90,000 to WVU to recommend design and to arrange for rights-of-way of a 6-station, 120-vehicle PRT. Another $1.3 million was awarded to JPL to manage the system.

Almost simultaneously, UMTA announced that it would assume overall supervision of the project to ensure reproducibility and national applicability of the system. Its first decision in that capacity was to terminate Alden's contract on the grounds that Alden had neither the financial resources nor the capacity to carry out a large development project. (In fact, they had only five full-time employees.) The agency also pointed out that Alden would not qualify for the competitive bidding because they had written the specifications. New specifications were drawn up and approved jointly by UMTA, WVU, and JPL.

On the basis of informal contacts made with industry during this period, JPL prepared a rough project cost estimate of more than $37 million, compared to the initial $13.5 million. UMTA had, in fact, budgeted about $20 to $24 million for the demonstration. Lacking detailed technical designs and faced with rising costs, UMTA told JPL to propose an alternative system costing $20 to $30 million. A PRT system that included five automated vehicles, guideway, three stations, software, tests and evaluation, and one maintenance facility was determined "sufficient to address UMTA's major program objectives of establishing technical feasibility while limiting the program cost."

In April 1971, DOT solicited the transportation industry for proposals to design and build the system. A number of aerospace companies responded. In May, UMTA let contracts for various components of the system to companies selected by JPL. The Being Aerospace Company was to build the PRT vehicles. A major aerospace company in its first venture into ground transportation, Boeing teamed with Alden (whose fundamental vehicle-steering design was retained). Sundberg-Ferrar was selected to design the passenger compartments.

Bendix Corporation was chosen for the command and control systems, with Systems Development Corporation named subcontractor to Bendix for the software. Frederic R. Harris, Incorporated, received the contract for design of power and guideway systems as well as for the stations.

Although UMTA expected JPL to perform the role of system manager and technical integrator, the separation of management and design of the PRT's complex elements reflected the traditional approach of transportation systems, i.e., buying them piecemeal instead of as a package. This proved detrimental to the complex integration of the PRT's elements, for which an aerospace type "systems" approach was almost mandatory.

For its part, Boeing's PRT bid was an outgrowth of the desire to diversify the aerospace company. They were also well aware that their aerospace expertise qualified them specifically for entering the field. They joked that the Boeing-designed Lunar Rover Vehicle (LRV) of Project Apollo was really the first PRT. In fact, in every phase of their participation in the project, Boeing's basic aerospace character was an important factor.

A test facility for the Morgantown vehicle was installed at the Boeing Aerospace Company's Kent Space Center in Seattle. Throughout the project,
assignments of personnel reflected aerospace experience; a Minuteman ground systems supervisor and Houston Space Center manager (responsible for Apollo engineering analyses) was ultimately selected PRT program manager; the LRV project manager and several LRV engineers were eventually assigned to the Morgantown project; from Boeing’s military aircraft program came the PRT products support engineering manager; in addition, aeronautical engineers were later attached to the Bendix group to manage the subcontractor. At its height, Boeing’s PRT team numbered about 200 people—all of whom had some aerospace background.

Shortly after design contracts were awarded, friction developed between UMTA and JPL and between UMTA and WVU. On the one hand, UMTA officials were skeptical of JPL’s cost and scope forecasts. JPL and Elias had envisioned vehicles for eight persons and 7.5-second headways, but DOT wanted larger cars (to justify the program to Congress) and 15-second headways. DOT also decided against providing each car with the capability of pushing a disabled vehicle off the guideway. This would have required more sophisticated steering and collision-avoidance designs, costing several million more.

According to Elias, however, it seemed that “DOT didn’t have faith in the technology; they weren’t taking advantage of the technology that was available... JPL said there was nothing they couldn’t do: they had gone to the moon.”

For its part, DOT thought JPL was falling behind in defining the system. “There was not enough of the ‘Let’s get moving’ industry attitude,” said one of the administrators of the program. Under strong pressure from Secretary Volpe to demonstrate the new PRT before the November 1972 presidential elections, UMTA was as anxious to start construction as they were to minimize costs.

After a year had elapsed without a contract, JPL and DOT still could not come to terms, and UMTA asked Boeing and Bendix to present proposals for systems management of the project.

By mid-1971, disagreement between UMTA and WVU had also increased, and the university was eliminated from all management decisions, although it continued in an “advisory capacity.” UMTA drew up a contract with WVU for implementing the project (none had previously existed). At this point, the Morgantown program was divided into three distinct phases in lieu of the original single integrated effort to develop a 6-station, 100-vehicle system.

In addition to the research and development demonstration—Phase 1A—the contract between UMTA and WVU outlined Phase 1B, which would ensure an operational 3-station, 45-vehicle system. It was also understood that following Phase 1B, WVU could apply for a capital grant (80 percent federal and 20 percent local funds) to complete the 6-station, 100-vehicle system. Included in the contract was a proviso that if WVU were not pleased with the system, UMTA would remove it.

In August 1971, UMTA selected Boeing to replace JPL as overall system manager of the Morgantown Demonstration Project. In a letter contract, Boeing agreed to retain the subcontractors already selected and to have five vehicles ready for demonstration by October 1972. Phase 1A began.

Phase 1A of the Morgantown Project

Following lengthy negotiations, Boeing and UMTA concluded an agreement for Phase 1A in January 1972. As defined in the final contract, the PRT system was to consist primarily of rubber-tired, electric-powered vehicles with “vehicle onboard command and control system” (VCCS); the guideway, with control and communication links; stations, including station computers; and a central-control computer. The PRT was to run either on fixed schedules or in response to passenger demand, at 15-second headways. Nonstop, direct service would be provided by computerized dispatch and control of all vehicles. The overall command and control system would incorporate a central computer, onboard controls, and an independent collision-avoidance system (CAS).

Limitations of time and money imposed by UMTA characterized Phase 1A and virtually prevented the use of aerospace “hardware” in the Phase 1A PRT system. The politically motivated pre-election deadline, for example, required a very demanding schedule. Similarly, in the interest of keeping costs down and despite Boeing’s project estimate of $44 million, which was based on more detailed design and analysis, the final contract for Phase 1A bore a price tag of $37 million. Several operational features of the system (e.g., revenue service equipment, guideway heating, operational softward, maintenance facility, etc.) were deferred to Phase 1B.

Attempting to meet the stringent schedule within budget fostered approaches that many considered undesirable in complex aerospace systems work: concurrent construction and design of the system’s major
elements and frequent use of commercial hardware. In September 1971, for example, ground was broken for the guideway—before the major vehicle and control parameters were determined.

Furthermore, the contract stressed using "existing state of the art technology and standard off-the-shelf components." By definition, this implied maximum use of traditional ground-transportation elements, which were particularly unsophisticated because of a state of the art technology and standard off-the-shelf components. In September 1971, for example, ground was broken for the guideway—before the major vehicle and control parameters were determined.

In spite of their experience and predilections, therefore, Boeing found they had to make some "painful" tradeoffs in order to reconcile initial capital cost against long-term cost effectiveness. Standard commercial hardware often had to be selected in lieu of custom-designed hardware, which would do the job better but which might cost several times as much. For example, UMTA encouraged less expensive brakes, axles, and motors. Ordered through commercial concerns, these parts had not undergone the rigorous testing usually given aerospace hardware and proved insufficiently reliable for a fully automated system. But the use of commercial hardware was also fostered by the realization that if the PRT concept were to have long-range economic viability—and thus widespread use—it must be producible for a cost in the range of 5 to 10 dollars per pound, midway between standard automotive technology and that of typical aerospace applications.

In April 1972, in preparation for the first demonstration, Boeing began test runs on the first five prototype vehicles at its Kent test track. The "election year hysteria" of trying to meet the October deadline forced shortcuts and limited systems testing. It also gave the public a false sense of progress.

Despite serious reservations of many responsible participants in the program, the PRT system was dedicated in Morgantown in October 1972. One UMTA official later remarked: "It was ridiculous . . . like putting five 'breadboards' in the field. Anyone who knows anything about R&D knows that what they [Boeing] tried to do . . . developing a totally new, automated, integrated system . . . couldn't be done in the time they were given." The breakdown of one of the PRT vehicles during the dedication was almost inevitable, and it was only a portent. For Boeing and UMTA it was apparent that intensive systems testing would be necessary to resolve the problems of the prototype system design. True, the objective of Phase 1A had been just to demonstrate the technological feasibility of the PRT, and this had been accomplished. But as Boeing's project manager noted: "While no one expected this phase to result in a mature commercial system, both Boeing and UMTA were surprised by the magnitude of the changes which would have to be incorporated before this concept could be translated into a public transportation system. Then, too," he continued, "in every development there comes a time to fly and let the real world define the problems which remain to be solved." The testing that followed the initial demonstration of the PRT was directed to defining those problems. It was shaped in part by a totally unrelated event that occurred during Phase 1A of the PRT: namely, an accident at San Francisco's Bay Area Rapid Transit System (BART), when an unmanned vehicle ran off the end of a track.

Because this accident on another high technology transit system was attributed to a flaw in the automated train control system, it generated a thorough review of the Morgantown PRT system's safety features. During the subsequent audit and major redesign of the PRT fail-safe systems, UMTA, Boeing, and Bendix managers were very conscious of BART's problems. Some lessons and experience were thereby transferred from one aerospace-influenced project to another.

In the spring of 1973, Boeing, Bendix, and outside experts conducted a thorough safety study. Boeing's study was comparable to the rigorous test programs in "fly before you buy" aircraft contracts. The test results confirmed the inadequacy of the system's reliability and safety, and they identified specific problems that had to be resolved before the system would be ready for public service. Most important of the safety features analyzed was the VCCS. During the ensuing shakedown tests and design review, major defects were uncovered in key components of the VCCS. In the communications and control system alone, Bendix uncovered 40 problems. Unacceptable failure modes were discovered in the guideway [collision avoidance systems] and in various vehicle components such as brakes and axles.

Ultimately, the VCCS that Boeing redesigned during Phase 1B represented the most significant transfer of aerospace technology to the PRT's hardware. While its individual components cannot be strictly considered aerospace technology, the specific application and packaging of the VCCS were, according to Boeing, based on criteria similar to ones important in missiles or aircraft.
Following the 1973 spring safety audit and its findings, Boeing deepened its test program. During this task, they approached the PRT system as they did any complex aerospace program. For example, they conducted extensive analyses to search out logic faults in the electronic systems: "fault-tree" analyses were carried out on both components and operational characteristics of the system and were rigorously documented.

In July of 1973, Phase 1A—the initial test and demonstration phase—was completed. Boeing had concluded that a substantially improved vehicle would be required and that the problems defined previously could be solved by applying aerospace rigor and disciplines.18

Throughout the PRT program, the most effective factor in the transfer of aerospace technology was undeniable the involvement of Boeing. During Phase 1A, experienced aerospace engineers brought aerospace disciplines and management techniques to bear on the program. Proceeding according to the concepts of “systems engineering,” they defined the total system and its performance requirements at the outset. They then used aerospace systems engineering techniques such as reliability and fault-tree analyses to establish subsystem and component-design requirements.

The technology of Phase 1B exceeded that of Phase 1A in only a few instances, e.g., in substituting redundant solid state relays for gravity-actuated mechanical relays. The big difference appeared in detailed mechanization of the design as a result of aerospace engineering, rigor, and analytical methods. Here again, Boeing was most instrumental in the transfer.

**Phase 1B**

In September 1973, UMTA allocated $20 million and authorized Boeing to proceed with Phase 1B: to place into public service a 3-station, 45-vehicle system. It was the first time during the program that the specific technical characteristics of the operational system were formulated; the specifications for Phase 1B were actually the first opportunity to define the end product on the basis of relevant tests and analysis. Previous specifications had been stated only in terms of general performance and design goals, many of which were unattainable.19

The Phase 1B specifications were considered "very sporty" for a totally new transportation system, however, and Boeing found several of them comparable to criteria that they might have to meet in aircraft. For example, safety requirements approached those of commercial aircraft, i.e., \( 1 \times 10^{-4} \) probability of accidental fatality per operational day. This translates to approximately one fatality per 100 million passenger miles, less than the existing record for buses and considerably less than for automobiles. Such a requirement was beyond the demonstrated state of the art in surface transit systems.

The system reliability was defined in terms of the probability that a passenger could call a vehicle and complete his trip within a specified time—96 times out of 100 or better. In some instances, 10-year service-life requirements were imposed, and operations and maintenance costs could not exceed $850,000 per year.

Finally, the system had to move 1,100 passengers in 20 minutes between stations. This demanded continuous dispatching of vehicles every 15 seconds.20

During the Phase 1B construction and installation of the 45-car system, Boeing redesigned every key element of the PRT vehicle and system. The following elements21 are identifiable transfers of aerospace technology:

1. A new VCCS—the "brains" of the vehicle—was developed by Boeing "with the same degree of engineering and quality control over design and production as if it were going to the moon." The $20,000 cost per unit is one-sixth of the cost of the vehicle, but the VCCS is vital to the objective of 100 percent automation and thus reduces operating costs, the most expensive factor in labor-dependent conventional systems.

2. The guideway CAS is based on the concept of redundancy. Two separate systems, one operated by the computer, the other by handwired logic, check each other continuously. If a conflict appears, the vehicles are brought to a safe stop. A computer-controlled management system prevents vehicles from being dispatched into conflicts on the guideway. In a sense this is a third independent system.

3. Standard railroad relays used in Phase 1A vehicles for onboard switching were replaced with relays used in spacecraft. The railroad relays were found to be unreliable when subjected to vehicle vibrations. The aerospace relays had high reliability and were a fraction of the size and cost of railroad relays.

4. A highly responsive, redundant hydraulic brake system was developed, using servo-valves from aircraft applications. The original automotive-type brake calipers were replaced with a design derived from BART technology.

5. Throughout, Boeing's manager of transportation systems encouraged use of more sophisticated technology to realistically address the PRT's design
requirements, where commercial components could not do the job adequately.

6. Axles were redesigned and aerospace-type process controls were imposed on the axle supplier to ensure a high quality product with the required system-life.

7. The real-time computer software developed for Phase 1B was comparable in sophistication to aerospace programs. Industrial software used extensively for process control and monitoring generally has a manual backup, but the PRT program had to respond to varying circumstances without manual intrusion. While PRT software was not as complex as Apollo software, it was designed to do all the same things on a smaller scale.

8. Boeing used an aircraft computer program to analyze the maintenance requirements of the PRT.

9. Military and aircraft standards were specified for selecting components. As in aircraft, certain components were designated "safe-life designed," and their mandatory use was specified in the maintenance manual. The manual itself resembles those used by Boeing for aircraft or missile systems.

10. Self-diagnosis, like that found in aerospace systems, was built into Phase 1B vehicles. Vehicle faults were relayed at once to the central computer. Redundant systems could propel the vehicles to repair facilities if problems were found in the primary systems.

As a prerequisite to production of the Phase 1B vehicles, Boeing had reviewed with UMTA all fault-tree analyses and hazard reports, focusing attention on safety and reliability. UMTA then had conducted a thorough review of the design and had awarded Boeing a contract for the first phase of production. For this task, Boeing also brought its aerospace experience into play:

1. The manufacturing manager was transferred from the Boeing 747 aircraft to the PRT vehicle. In his new role, he used virtually the same techniques of production scheduling, crew loading, budgeting, and plotting of learning curves that were used for aircraft and missiles.

2. The manufacturing facility in which the vehicles were assembled was the same used to build the supersonic transport (SST) mockup; the vehicles shared the building with another prototype airplane.

3. Engineering quality analyses, similar to those performed in aerospace work, were performed on key PRT vehicle components. For example, as items arrived from the supplier, assemblies were dismantled and tested for tolerances and workmanship.

By September 1975, Boeing had extensively tested and debugged all 45 vehicles at the Seattle test track and in Morgantown. Throughout this task they relied on "highly systematic" approaches (the use of formal test requirements, plans, and analysis reports) that are not exclusive to aerospace but are more common to that discipline than to mass-transit.

Following the tests, UMTA accepted delivery of the system, and Boeing signed a contract with WVU for assistance and training during the first year of operations. UMTA also approved $4 million in capital grants for additional facilities, first year operating costs, and preliminary design for a Phase II expansion, whose approval was pending as of the end of 1976.

This marked the formal completion of the demonstration phases of the Morgantown PRT project. According to the agency's Morgantown program manager, Boeing's performance was one of the brightest spots in the program. He further considered that the aerospace input to Phase 1B—especially systems approaches and discipline—had saved the project.

Before the Morgantown demonstration project was completed, UMTA had initiated a so-called "High Performance" PRT demonstration. Lessons learned in Morgantown may be transferred to this second-generation PRT most directly through the participation of Boeing, which won one of the three contracts awarded by UMTA for preliminary designs.

Potential for Future Use of PRT Technology

Many aerospace companies (e.g., Boeing, Rohr, Westinghouse, LTV, Bendix) have made major investments in the mass-transit field. It was a natural market for them, and national emphasis on solving urban transportation problems sustains hope that it will eventually be a large, dynamic market.

The developers of new transit systems, however, have had serious difficulty in finding and convincing potential customers: transit operators, private investors, city planners, or consultants to the city. In general, the problem stems from several factors. First, transit operators are frequently preoccupied with the problems of existing capital facilities. Their economic concerns are described by their constant search for operating subsidies. Advanced technology is beyond their interest or finances.

Second, city planners are not well acquainted with the potential of new transit systems. They instinctively choose systems with the lowest initial acquisition cost rather than with the lowest life-cycle cost, the benefits
of which accrue only in future years when they are likely to be out of office.

Finally, communities choose one system over another on the basis of consultants' recommendations. Reflecting the interests of their political mentors, consultants may be conservative and reluctant to recommend what is not operating and available. They tend, therefore, to steer their clients away from the R&D business with its attendant risks.

Boeing and other aerospace contractors have tried to market total systems on a "turnkey basis," that is, selling to communities a completed transportation "package," ready for operations. From its experience, Boeing concluded that buyers aren't ready for this approach to innovative design and installation. The customer seems to care little about technology and management processes, focusing instead on his immediate needs: Do I get there when and how I want and for what I want to pay? Such questions are easier to discuss in terms of existing products rather than future systems with unmeasured benefits. It is likely that the market for such systems will develop only after the system supplier and the buyer can agree on language of long-range benefits.

In the interim, Boeing's bid on the high-performance PRT reflects optimism that PRT's are a part of the future of transit and that the government will continue to support this technology.

In fact, the future of the PRT would seem to depend on several significant factors, only one of which involves the technology itself: first, successful operation at Morgantown; second, public acceptability of the characteristics of automated systems; third, more progressive city planners; fourth, federal policy permitting PRT eligibility for capital grants; and finally the extent to which automobiles are excluded from the inner city.

Critical Assessments of the Morgantown PRT

As suggested throughout this study the major targets of criticism directed at the Morgantown PRT were its cost, complexity, and technical problems—especially when compared to its limited use in a small-town environment. At first glance, the criticisms seem valid. At $64 million, the Morgantown six-mile system, serving a community of 40,000, is expensive by any standard. The case against it is even stronger in the face of critical, unsolved transit needs of cities 10 to 30 times more populous. Unquestionably, the PRT is also complex and relies heavily on highly sophisticated components.

Nevertheless, there are several valid counterpoints that are often obscured by the controversy and ignored by avid critics of the PRT project.

First, the Morgantown PRT was a "demonstration" project that attempted to introduce a new solution to one of the nation's many transit problems: the congested inner city or small urban area. No economically viable approach had been advanced to date. The PRT was conceived not only as one community's transit system, but also as an operating test-bed to provide empirical data on production cost, performance, reliability, and public acceptance.

These are legitimate functions of a demonstration project, which, in turn, is an effective means whereby the government may transfer technology to the other markets. The government correctly assumes that role where the cost of the technology would preclude its introduction by industry alone. Measured by these criteria, the Morgantown PRT represents a significant achievement: a totally new application of advanced technology to an operating urban system, which may provide a cost-effective solution to mass transit in the future.

Second, the Morgantown PRT was typical of development projects, for which the costs and technical outcome are unpredictable. It was inherently subject to costly and extensive testing and redesign. In fact, UMTA made no great claims of predictability to Congress. Less than six months after approval of the Morgantown demonstration project, Robert Hemmes, assistant administrator for program demonstrations, said in appropriations hearings of the 1972 fiscal year:

Our estimates began at $1 million a mile. But as more was learned about these systems, they have followed the same pattern of cost escalation that all high technology projects have followed. That is, at first there are many considerations that are not in the estimate because we haven't encountered those problems yet. Later the estimate grows as we build the system and we encounter the problems.

The $1 million a mile is for a system without switching and merging. When we added the switching and merging capabilities, the estimates were $5 million a mile. Now that we have encountered problems, which was to be expected, and are following the familiar pattern of technology development in other past programs such as aerospace and defense programs, the estimates have grown to $7 million and in some of the more complicated ones to $9 million a mile. But if we carry 7,000 people per hour past a point at $9 million a mile, this would compare favorably with the construction of an eight-lane highway carrying the same number of people. The highway, of course, isn't very complicated in technology but it requires so much right-of-way in congested urban environments that it could be much more expensive than people-movers.86

Of course, the "$9 million a mile" also proved gross-
ly underestimated. But to those critical of the demonstration’s $64-million price tag, UMTA officials maintained that it was entirely justifiable and comparable to any research and development program as innovative as the PRT; its effective 18 percent cost overrun was actually far less than many complex R&D programs.

To put the Morgantown PRT in perspective, its cost should be compared to the development costs of other such projects or competitive mass-transit systems. Although the PRT has been expensive to build, its complete automation reduces its operating costs (while permitting it to operate on 24-hour demand), thus making it far less expensive over the long term than a bus system of the same capacity and service capability. (The break-even point between the two modes is estimated at about seven years.)

Nevertheless, UMTA officials realized that the high initial cost of the PRT would militate against its widespread replication. Now that the technology has been virtually proven, UMTA expects that the next generation system will carry lower cost of replication.

Despite these justifications, however, it was the program’s mounting cost and its unenviable distinction as one of the banes of UMTA’s relationship with Congress that made it something of a “programma non grata” in DOT. The Congressional Appropriations Committee became increasingly critical of PRT’s cost overruns. The issue was further confused by the bizarre spectacle of WVU threatening to invoke its contract and compel DOT to remove the whole system (at an additional cost of $7 million) if the agency did not fund completion of the system to its original scope.26

Of course, the problem of convincing Congress to fund development projects was not unique to UMTA. Backers of the SST bear witness. It also illustrates the critical relationship between such requests and current national priorities. Congress is more easily convinced when a request seems to support a stated national goal; it is less easily swayed when other goals take precedence or funding is tight. At the same time, the 1964 legislation creating UMTA provided for “research, development, and demonstration projects in all phases of urban mass transportation.” The agency had a mandate to conduct such programs, and Congress had a responsibility to understand what they entailed.

A third factor which should be kept in mind is that the system’s complexity was a function of its competition with the automobile for public acceptance. At the least, the system’s acceptability depended on maximum safety and reliability, maximum convenience and comfort, and minimum operating costs. To achieve all this within a specified number of dollars and level of complexity was a major challenge.

Fourth, a complex R&D program cannot be subjugated to the vagaries of internal politics without substantial adverse impact. When politics enter into technical decisions, long-term benefits are almost inevitably sacrificed—at great cost—to short-term gains. Involved in the process, the PRT’s technical people resented the politically inspired decisions of the administration, which adversely affected the program.27

On another level, past government experience with complex R&D programs had also proved that sound management is the key to success. An agency lacking such expertise, therefore, should not assume the role of systems manager. In the case of the PRT, stresses within the program were reflected—and intensified—by the management weaknesses in the Federal Government. During the first three years, for example, the Morgantown PRT had several project managers, was shifted between two administrators, and was a major cause of the resignation of an assistant administrator.

Finally, in evaluating the Morgantown project, it should be remembered that the PRT was an attempt—one of few—to get the auto out of the city center. It may not be the optimum solution, but in the absence of any viable alternatives, it deserves full trial and evaluation. Although it is initially expensive, its automation may ultimately yield a more favorable cost picture over its entire life. Boeing’s Morgantown PRT project manager noted: “The problems encountered at Morgantown in this contract are lessons learned and were worth the money they cost; there was no other way to gain the experience. The tragedy of Morgantown will be if it suffers a premature demise brought about by political considerations and critics who do not know how to run or evaluate a large scale technology experiment.” 28
Notes

1. Interview, Dr. Samy E. G. Elias, chairman, Industrial Engineering Department, West Virginia University, 19 November 1974.
2. Ibid.
3. Ibid.
6. Elias interview; " 'Morgantown's People Mover' "; Pastor interview.
8. Interviews with these Boeing Aerospace Co. management personnel at the Kent Space Center, Seattle, Washington, 14 October 1974: T. M. (Scotty) Davidson, Morgantown project manager; John W. Allen, Morgantown systems integration and test manager; Jack H. Keeney, Morgantown product support manager; and Harvey Iverson, Morgantown manufacturing manager.
9. Ibid.
10. Elias interview.
11. Pastor interview.
12. Elias interview; Pastor interview.
16. Pastor interview. The UMTA official was also speaking from his own extensive experience in the aerospace business and as head of a new department in the Transportation Systems Center (formerly under NASA), whose early assignment was to provide technical support to UMTA for Morgantown.
17. Davidson letter.
18. Interviews with Boeing Aerospace managers; Davidson letter.
19. Interviews with Boeing Aerospace managers.
20. Ibid.; Davidson letter.
21. Ibid.
22. Interviews with Boeing Aerospace managers.
23. Davidson letter.
24. Interview, Steven A. Barsony, director, Morgantown Division, UMTA, 21 January 1975.
26. The university subsequently accepted the Phase IB system, signed a contract with Boeing for support services during the first year of operation, and looked forward to possible capital grants to extend the system.
27. It should be noted that they felt equally frustrated by a "cynical and headline-seeking press," which they believe accentuated the negative.

Liquefied Natural Gas Tankers

Susan Frutkin

EDITOR’S COMMENT

The second of Susan Frutkin’s studies is timely in its connection to U.S. energy problems. Building on a foundation of research and economic analysis that Booz Allen Applied Research performed in 1973, she conducted numerous interviews and then refined and extended the story to describe processes involved in the transfer of aerospace technology to liquefied natural gas tankers. While she has emphasized the importance of individuals and organizations in developing liquefied natural gas (LNG) technology, she is no less careful to present relevant technical material.

Frutkin has made several points in explaining why aerospace technology was used on LNG tankers. The techniques of storing and handling cryogenic substances, developed by aerospace contractors in the last two decades, were readily adaptable to use at sea. Many of the safety and control devices for handling liquid gas were taken from the missile and space industry. The fact that General Dynamics, which owns Quincy Shipyards where many LNG tankers are built, is a large aerospace contractor induced them to use their aerospace engineers. Much of the technology of potential use, it turned out, was too sophisticated or was unsuitable. Frutkin implies that some resistance developed because space technology was imposed on nautical architects and engineers with different traditions and orientation. In the low-temperature containment system, 9 percent nickel steel was replaced by an aluminum alloy, apparently because it was more familiar to the aerospace engineers. Fracture mechanics, a subdiscipline of the mechanics of materials used frequently in aerospace industry, was applied to test ship structures in advance. The method helped to certify the safety of the ships and thus to gain rapid approval from federal agencies, which were charged with confirming guarantees and subsidies. Aerospace technology did not bear the blame, but its reputation may suffer from a 1973 explosion of an LNG storage tank on Staten Island, which killed some 40 people. If the LNG program is deemed unsafe, there will be no gain from the cancelled aerospace technology within it.

Frutkin’s major point is that space technology was transferred to LNG tankers because management insisted. The corporate commitment of General Dynamics to aerospace methods moved people from its Convair Division to Quincy, from spacecraft to ships. That commitment overcame traditional differences between workers from Quincy and Convair and permitted more or less harmonious relations while producing the tankers. The arrangement fashioned a unique aerospace-nautical project.

Profit is still the definition of success in the U.S. capitalist economy. Could LNG ships have been built profitably at Quincy without aerospace contributions? We know at least that they could have been built, because LNG tankers have been sailing under foreign flags for almost two decades. Yet many results of tapping General Dynamics’ aerospace expertise contributed to the safety and utility of these large ships. We fear that one cannot separate the aerospace component of economics from the rest of the profit (or loss) of LNG tankers. We will know if the project has been successful economically only in future years. If it is, the energy crisis in America will have played a major role, but space tactics will share a measure of the success.

Introduction

In the late 1960s, several factors combined to stimulate U.S. interest in LNG tanker development. A rapid decline in U.S. shipbuilding, an unfavorable balance of payments, and a strong domestic cryogenic capability coincided with decreasing energy supplies and the thrust for a cleaner environment.

As awareness of an impending “energy crisis” grew in the sixties, abundant and clean natural gas became an obvious candidate for petroleum substitution. Until then, U.S. gas supplies and reserves were sufficient to meet existing domestic demand. After the mid-1960s, however, energy consumption rose, while exploration and development of U.S. natural gas resources were discouraged by price ceilings imposed by the Federal Power Commission (FPC) in 1954. Although Alaskan fields were opened, importation to the lower 48 states was inhibited by the expense of transporting gas and by a provision of the Jones Act that requires transport in unsubsidized U.S. flagships, of which none designed to carry natural gas were yet in service. By 1970, U.S. demand for natural gas exceeded domestic supply by five percent, and the Federal Power Commission estimated the deficit would reach approximately 40 percent by 1990.

The main sources of developed natural gas reserves are Algeria, Australia, Borneo, Indonesia, Iran, Libya, Malaysia, Nigeria, Trinidad, USSR, and Venezuela. With one exception, all are separated by oceans.

Susan Frutkin, formerly with Booz Allen Applied Research, Bethesda, Maryland, now with American Petroleum Institute, Washington, D.C. 20037.
from the United States and the other two major natural gas markets: Europe and Japan. By definition, therefore, increased demand for natural gas stimulated import programs and increased requirements for ships to transport the gas by sea.

Because the ratio of the volume of natural gas at sea-level pressure and room temperature to liquid natural gas is 618 to 1, the viable economic way to transport the gas is in its liquid state. It is liquefied by cooling to its boiling temperature of about \(-258^\circ\) F; Thus LNG is characterized as a "cryogenic" substance. Taken together, the properties of LNG produce a maze of technical problems in handling, which arise from extreme temperatures, high volatility, troublesome fluidity, metallurgical sensitivity of containers, hazardous chemical properties, and rigid requirements for transfer and conversion of LNG. These characteristics impose design criteria on a ship to a degree not approached by any other commercial cargo. They make LNG tankers not only technologically unique but also more expensive than any other cargo ship of or near their size.

**Technological Requirements of the LNG Tanker**

During ocean transport, LNG must be maintained as a saturated liquid, i.e., at cryogenic temperatures and near atmospheric pressure or close to the point at which it turns to vapor. Because cryogenic temperatures are far below the brittle fracture point of ordinary ship steel, contact with the hull risks serious damage and even imperils the ship in heavy seas. In addition, gas leaks must be carefully controlled to avoid potentially explosive conditions.

The critical elements of an LNG tanker, therefore, are the cryogenic systems, of which the containment system is the major element. The containment system is principally a holding tank or tanks, generally described by its components and configuration: primary and secondary barriers, high performance insulation, instrumentation, shape, and interfaces with the ship's hull. Since the first work was started on these ships, several different versions have been developed that comprise two generic designs of the containment systems: (1) free-standing tanks—prismatic, cylindrical, or spherical versions of self-supporting tanks utilizing various barrier materials and insulation but all structurally independent of the ship's hull; (2) membrane tanks—thin layers fitted into a tank composed of the ship's hull and load-bearing insulation.

Safety and control systems are as important as the containment system. LNG tankers typically contain sophisticated leak-detection devices, fail-safe systems, pressure and temperature sensing and control instrumentation, vent and pressure-relief systems, and boil-off vapor disposal (often integrated into the propulsion system as boiler fuel), in addition to ordinary fire and safety equipment. Handling and storing LNG involves other special systems and equipment for making tanks inert; drying, cooling, warming, and aerating tanks; pumping, loading, discharging, and measuring cargo.

While not related specifically to the cryogenic systems, the relatively low density of LNG and the containment system give the ship an unusually high freeboard. Attendant problems of stability must be counteracted by supplementing ballast, for which space is limited, with special stabilizers.

Finally, all elements of the tanker that come in contact with the LNG must be compatible with low temperature conditions. They must be designed to minimize thermal dimensional changes and stresses, and they must be durable in the marine environment as well. The net result is a unique, single-purpose ship, whose primary design criteria are safety-oriented, and whose price exceeds $100 million (for a 125,000-cubic-meter vessel).

**The Context of Operations**

A typical project for importing natural gas to the United States requires a comprehensive system of which the tanker is only one element. The first phase of the system involves extraction, field processing, pipeline transportation, compression and liquefaction of natural gas at facilities near the source of supply. The marine transportation phase brings LNG in tankers to receiving terminals at a U.S. port (usually near highly populated market areas). There, at shoreside terminals, the LNG is unloaded, transferred, stored, and revaporized to natural gas for distribution to consumers (who may not be in the same state).

This comprehensive project represents a significant financial commitment. The costs of implementing one Algerian-U.S. project for importing 1 billion cubic feet of LNG per day over 25 years included investments in shoreside facilities (gas wells, gas-gathering system, processing plant, pipeline, liquefaction plant, storage and loading facilities) and were estimated to exceed $1.1 billion; the additional cost of the requisite nine LNG tankers exceeded $800 million.

In addition to the costs, the complexities and diffi-
cultures in bringing about such a project have been aptly compared to the "Perils of Pauline." Involved are coordination, agreement, and approval of a staggering array of organizations and individuals concerned with investments, safety hazards, or political and economic implications of importing LNG.

At the outset, gas supplier (company or government), shipowner, shipbuilder, ship lessee (which can be many different people or institutions), gas storage companies, distributors, utilities, bankers, and insurance companies must work together. To implement the project and certify the ships also necessitates meeting standards, filing applications, and gaining approval of a multitude of public authorities. These include the American Bureau of Shipping (ABS), U.S. Coast Guard (USCG), Federal Power Commission (FPC), Environmental Protection Agency (EPA), Commerce Department (Bureau of Customs, Measurement of Vessels), Maritime Administration (Mar Ad), Federal Communications Commission (FCC), International Telecommunications Commission, Army Corps of Engineers, Department of Interior, State Department, Department of Transportation, International Convention for the Safety of Life at Sea, Intergovernmental Maritime Consultative Organization, state and local governments and their agencies (including port authorities, energy and environmental control offices).

Complicating this process still further, public agencies often hold hearings, thus involving a multitude of private and public interest groups.

In all, over 60 professional and governmental entities, plus private interests, could be involved in a single project to import natural gas into the United States.

Potential for Transferring Aerospace Technology to LNG Tankers

The element of the LNG tanker most suited for adoption of aerospace technology is the cryogenic containment system. The big space and missile programs of the 1960s considerably advanced technique in cryogenic engineering. It should be noted that much of the cryogenic work conducted for the space program involved improvements in technology that originated in traditional cryogenic industries, i.e., chemicals, energy, food, and metallurgy. The designation "aerospace technology" is therefore applied with some caution.

Significant space-inspired advances from handling cryogenic substances were made in insulation, metallurgy, adhesive welding, instrumentation (e.g., custom transfer system developed for Apollo spacecraft to measure and test liquid fuel taken on), analytical methods (stress analysis, fracture mechanics, thermal dynamics), and systems management.

In the important area of insulation, several aerospace suppliers developed significant innovations. Notable were the Martin Marietta Company (internal honeycomb insulation using a bleed and vaporize concept to create a pressure barrier), Rockwell International (wet-wall urethane insulation, now licensed to French and Japanese concerns), and McDonnell Douglas Astronautics Company (three-dimensional fiberglass matrices, reinforced urethane, internal insulation systems). All were developed in conjunction with the space program, and all have potential LNG tanker application; however, none has yet been approved by the U.S. Coast Guard for use in ships.

Each of the organizations and individuals that are involved in coordinating, financing, and approving a natural gas import project is a potential "inhibitor" or "promoter" of technology transfer. Because they are most often involved on account of the considerable financial commitments or safety hazards, they tend to approach technological innovations conservatively. Those who finance such projects place a high premium on maximizing returns and minimizing costs and risks. Those concerned with safety seek assurance through time-tested guarantees of performance. Economics and safety may therefore be decisive factors in transferring aerospace technology to the LNG tanker.

At the same time, political and social problems, delays, uncertainties, long lead times, and long-term advance commitments may greatly influence the potential for transferring technology, and they may ultimately outweigh both technical merits and other promoters of transfer.

Another group of potential transferors is less directly affected by these influences. Subsystem contractors, material and hardware suppliers, ship designers, and patent holders are all participants in the LNG tanker development but are one step removed from the financial and regulatory institutions. Nevertheless, to the degree that they are subject to the shipbuilders' specification and wish to do business in U.S. yards, they too are subject to the same constraints.

Evolution of LNG Tankers

As noted, the distinguishing feature of LNG tankers is the cryogenic containment system. The evolution of these ships is therefore reflected in its changes.
The earliest development of LNG tankers was done in the United States. In 1952, energy and shipbuilding interests experimented with balsa-lined, free-standing tanks fitted onto a 6500-cubic-meter barge to transfer LNG from Louisiana to the Chicago stockyards. This first attempt to transport LNG by water was a relative failure; tests showed surface damage to the wood insulation resulting from direct contact with the LNG.

Between 1957 and 1959, an American gas company, a shipbuilder, and a naval architect jointly ventured with the British Gas Board to prove the feasibility of large-scale ocean transport of LNG. In this experiment, a 5000-cubic-meter dry cargo ship was fitted with five aluminum alloy balsa-polyurethane insulation freestanding tanks. This ship carried the first oceangoing LNG from Louisiana to England. The experiment was terminated in 1961 after six successful voyages.

For more than a decade following these early projects based in the United States, virtually all design and development of LNG tankers was conducted in Europe. Lack of U.S. involvement stemmed largely from the lack of need or incentive to import foreign gas. At the same time, the greater demand in Europe and French interest in exploiting Algerian resources stimulated development of LNG tankers abroad.

During this period, European energy interests made several refinements, most significant of which were in insulation materials, metal alloys, tank shape, barrier construction, utilization of boil-off as auxiliary fuel, and submerged cryogenic pumps. European interests patented a number of LNG containment designs, on which were based all LNG tankers built or under construction through 1975. Furthermore, until 1972, all 18 LNG tankers ordered worldwide were either delivered from or under construction in European yards.

There are indications that several innovations utilized in the European tanker designs reflected transfer of U.S. aerospace technology abroad. While the full extent of this transfer has not been documented, some of the major concepts, materials, and processes can be traced to the United States. Among these, for example, was a submerged cryogenic pump, considered a major step forward in LNG cargo-handling technology. The pumps were placed in two ships that were part of an all-European energy project and had been adapted by a U.S. supplier from similar designs used in aircraft. Much of the hardware for the ships was procured in the United States.

Other examples of transfer of U.S. technology to the European designs are evident in the Norwegian Kvaerner-Moss spherical tank design, later licensed to General Dynamics for production in the United States. The tank support ("ring equator") is comparable to that used for the Saturn V oxidizer tanks. In addition, metal alloys, welding techniques, and insulation materials used in the ships were all supplied by U.S. companies.

It was not until 1972 that the first order for LNG tankers was placed in the United States. Since then, a total of 16 ships has been ordered in four U.S. yards. While all are being built under license to European patent holders, the potential for transferring U.S. aerospace technology existed nonetheless. To see how such transfer may have been achieved, Booz Allen Applied Research selected the case of Quincy Shipyard's LNG tanker program for in-depth research and analysis. Quincy was chosen because (1) it was the first U.S. yard to conclude a contract for LNG tankers and is constructing half of the tankers on order in the United States now, and (2) it is a wholly owned subsidiary of General Dynamics, a major aerospace conglomerate. It therefore presented an excellent opportunity to study interaction between the aerospace and marine industries.

Transfer of Aerospace Technology to the Quincy Shipyard and to General Dynamics' LNG Tanker

General Dynamics acquired Quincy Shipyard in 1964. A steep decline in ship orders over the next several years culminated in the loss of several large Navy contracts for which Quincy had been a prime contender. Work on the shipyard's current orders was to be completed by 1972, and General Dynamics considered closing the yard after that. (Several thousand workers were actually laid off before work on LNG tankers was eventually begun.) Among alternatives for revitalizing the yard was the possibility, pursued by both Quincy and General Dynamics' corporate management, of entering the LNG tanker market to exploit the predicted rise in international energy trade.

Simultaneously, representatives of European patent holders were trying to market their designs worldwide. In the case of the Moss-Rosenberg shipping group, holder of the patent on the Kvaerner-Moss LNG spherical tank system, their small yard was limited to building one ship at a time.

In spite of the obvious potential, however, the considerable financial investment and risk in the new venture prompted General Dynamics to undertake two years of study and evaluation before making a com-
commitment and signing a license agreement.

The first phase of the study included a thorough appraisal of all recognized LNG containment systems. This review was made under the direction of the general manager of Quincy Division and in cooperation with the General Dynamics corporate vice president of Engineering and Program Development. Thereupon Quincy selected the Moss-Rosenberg spherical tank system as most readily adaptable to the yard's capabilities. The decision was based principally on the fact that alternative, membrane systems were labor intensive, a distinct disadvantage to U.S. yards, where labor costs were not competitive with foreign yards. By contrast, the Moss-Rosenberg tank was not only less labor-intensive, but it was also considered more predictable in operation and easier to maintain.

In mid-1970, Quincy Division proposed to the General Dynamics Board of Directors that the company enter the LNG tanker market. Further review of the containment system design and a Det Norske Veritas analysis culminated in the signing by General Dynamics of an exclusive licensing agreement with Moss-Rosenberg.

For still another year, Quincy management conducted extensive studies to support their request for corporate financial backing necessary to enter actively the LNG tanker market. A market strategy study indicated that LNG tankers were a good long-term business opportunity and had the highest commercial value per square foot of any kind of ship under consideration. Manufacturability and facility analyses were also conducted by several shipyard engineers, working with an engineer who had experience both in the Douglas Aircraft DC-9 program and in Litton Industries' automated shipyard at Erie.

Finally, structural risk analyses—which proved to be a crucial determinant—were performed on the design of the containment system. An interdisciplinary team was formed for this effort, which included naval engineers and aerospace engineers with experience in cryogenic structures and metal fracture mechanics. The latter were "borrowed" from General Dynamics Convair Division, where the group's leader had participated in the Atlas-Centaur program. The team concluded that the Moss-Rosenberg design was well "within the state of art" and could use off-the-shelf hardware in "everyday use." This was the first of many instances during the company's LNG tanker production program in which the Convair Division was called upon for assistance and in which analytical methods were used effectively.

In spite of the team's convincing arguments, however, corporate approval might still have been withheld had Quincy's efforts not coincided with Federal Government incentives. The Merchant Marine Act of 1970 made bulk-carrying vessels eligible for the first time for construction and operating subsidies and construction loans and mortgage insurance. In addition, the Internal Revenue Service authorized investment tax credits for the first time for owners of tankers in international trade. Devaluation of the dollar in 1971 was an additional mitigating factor.

Applying these advantages to LNG tankers was not automatic, however. LNG tanker subsidies, for example, required MarAd approval, which was slowed by the cost of LNG tankers, considerably higher than cargo ships of the same size. Application of the 45 percent construction differential subsidy (CDS) to a number of LNG tankers costing almost $100 million each was clearly beyond MarAd's budget. Quincy executives worked closely with MarAd administrators (whom they characterized as "creative and entrepreneurial bureaucrats") to arrive at an arrangement whereby LNG tankers would be subsidized to the level of the most expensive conventional ship that already qualified. Ultimately, General Dynamics received a 23.7 percent CDS on its first three LNG ships.16

Although less significant as a direct economic incentive, a three-phase support program was initiated by MarAd in 1971 to reinforce tanker subsidies and to further facilitate all LNG import projects. At least one rationale behind the effort was the desire "to capitalize on this nation's know-how in cryogenics based on space and missile program experience. The U.S. aerospace industry has extensive technological capability which is not now being applied to Marine systems."17 MarAd officials calculated that, because of the highly developed U.S. cryogenic support industries, with technology that could be extended to design, fabrication, and installation of shipborne cryogenic systems, "it would appear that certain LNG cryogenic containment systems can be more competitively built in the United States than elsewhere in the world, provided that standards and continuity of programs are established and maintained."18

The first phase of MarAd's program consisted of testing and refining (European) containment systems. Eventually projects were initiated that included a liquid sloshing measurement, tank design, materials testing, leak detection, and design of instrumentation for custody transfer, the last at General Dynamics' request.
The second phase of MarAd's program was a short-term effort to reduce the economic risks inherent in LNG shipbuilding. An economic risk analysis was conducted, the results of which predicted a decline in demand for LNG tankers by 1985–1990. Shipbuilders were also encouraged to identify high risks and high costs that could be reduced through a shared R&D program.

The third phase was to have been a long-range R&D effort directed to reducing costs and ameliorating risk in second generation containment systems through the use of U.S. (aerospace) cryogenic technology. This phase was never fully implemented due to the pessimistic conclusions of the economic risk analysis. Consequently, these conclusions were reinforced by a shift in national priorities from clean energy to energy self-sufficiency. Nevertheless, MarAd initiated several R&D cost-sharing projects with companies already working on advanced cryogenics developments (two of which were Rockwell International and Martin Marietta, whose insulation designs were noted above). MarAd also supported a small program for transferring experimental cryogenic technology to shipbuilders (essentially information dissemination) from the Cryogenics Division of the National Bureau of Standards.

In mid-1971, the General Dynamics board of directors approved entrance into the LNG tanker market and committed roughly $40 million in capital investments to Quincy Shipyard Division. Two 900-foot by 150-foot basins and an 850-ton lift crane to install containment tanks in the ship accounted for most of the funds expended in the LNG tanker program.

Following General Dynamics' decision to enter the LNG tanker market, the containment system design was subjected to rigorous fracture-mechanics analyses (based on principles developed during the company's work to resolve F-111 problems), and refinements were made in design criteria. According to Quincy's chief development engineer in charge of performing the stress analysis, "this whole design procedure was unfamiliar in shipbuilding. Without the aerospace industry, fracture mechanics would not have been developed to the point of anyone thinking of invoking it as a design criterion for ships. It was beyond the state of the art in ships, but not in aircraft." The analysis assured a structurally sound ship, a conclusion that was of value because General Dynamics' 125,000-cubic-meter LNG tankers were larger than any previously built.

The frequent resistance to transferring technology, even within a corporation, is illustrated by the observation of one of the participants that Quincy was "forced" to seek and use the advice of its sister divisions (Convair and Electronics). The shipyard (traditionally production-oriented, with a very small engineering staff) drew on the aerospace division's extensive engineering talent, which included 150 metallurgists alone. As we see below, a successful working relationship eventually developed between the divisions.

Among the changes made as a result of the analyses was the substitution of an aluminum alloy, familiar to the aerospace engineers, for the nine percent nickel steel used by Moss. Alcoa was then hired to conduct additional fracture-mechanics evaluations needed to obtain U.S. Coast Guard and American Bureau of Shipping approval for the spherical, aluminum tanks. These tests also provided "objective" evidence in support of General Dynamics' applications to MarAd for subsidy and insurance guarantees.

On 19 September 1972, three affiliates of Energy Transportation, Inc., signed a contract with General Dynamics for three 125,000-cubic-meter LNG tankers. The ships will be chartered to Burmah Oil Tankers, Ltd., for carrying Algerian gas to the U.S. east coast.

At the end of contract negotiations, a special 10-man cryogenics group was formed at Quincy Division. An aerospace engineer with 15 years of experience in large missile programs at two companies was selected to head the group. Given a free hand to transfer the requisite engineers from the company's other divisions to Quincy, he brought together a team of aerospace engineers with expertise in cryogenics, electronics, and thermal dynamics. He also included several marine engineers in a conscious effort to integrate the new team with the shipyard's personnel. Ironically, a major problem in transferring the aerospace engineers to Quincy was convincing them to move from San Diego to the east coast. Of the 10 men asked to transfer, only two consented.

The potential transfer of aerospace technology to the LNG tanker was realized through ties of the cryogenics group to the company's aerospace-oriented divisions. The cryogenics group redefined specifications and supervised procurement of all cryogenic hardware for the three ships. (Only the piping was provided by Quincy.) In many instances, the team's aerospace experience was used. For example, data and methods developed in the space program to calculate heat
transfer coefficients were used in selecting heat exchangers. "Redundant" pumps assured fail-safe operation of the cargo system.

Similarly, much of the hardware selected for the tanker reflected advancements in aerospace use beyond basic concepts developed in other cryogenics industries. Examples include submerged cryogenic pumps and heat exchangers (discussed above), strain gauges, capacitance probes, densimeters, stress gauges, Teflon gaskets, butterfly valves, and seals. Suppliers were both aerospace and nonaerospace companies; in a few instances, the former were eliminated from competition on the basis of price; in others, companies with aerospace orientation were selected over the low bidder in technical review.

High costs, design complexity, and lack of approval by the Coast Guard mitigated against use of some of the more advanced aerospace developments. Notable among them were superinsulations, composite materials (e.g., boron fiber and graphite fiber for strengthening and tank supports), and flexible metal hoses (for lines to spray LNG into cargo tanks). Three of the superinsulations applicable to LNG tankers were noted above. General Dynamics had also developed a superinsulation for satellites under a NASA contract. This high-performance, multilayer insulation, with small tufts of dacron needles bonded to one side of a radiation shield, was considered unsuited for use in an LNG tanker. Insulation for satellites demands reliability over a short life, minimum weight, and reflectivity. The LNG tanker, on the other hand, requires insulation for convection and conduction of heat, reliability for up to 20 years of repeated use, and few weight limitations. Initial paper studies and tests to verify the insulation that was finally used in the General Dynamics tankers (a cheaper, more conventional urethane substance) were developed by the Convair Division. However, some basic engineering principles used in the company's superinsulation were also applied.

The aerospace background of the cryogenic team was further evidenced in its greater tendency toward formal documentation, quality control, full-range component and system pretesting, and computerized testing than was usual in shipyards. In some instances, these differences also grew out of differences in the marine and space environments. For example, extensive testing and quality control were often required for untried aerospace components, because it is impossible to retrieve and repair failed hardware in flight. By contrast, the shipbuilding industry benefitted from time-proven components and the ability to perform maintenance afloat. The cryogenics group at Quincy did pretest the LNG tanker's piping and valve system (though not by component) to detect potentially serious leaks. A computer program developed for aircraft analysis by Convair of Fort Worth was also used to determine the temperature distribution and the quality of steel in the inner hull.

During construction the cryogenics group was relatively "self-contained" and had only "selective" contacts with the rest of the shipbuilding staff. A participant commented that the relationship between the two at the yard was characterized by the aerospace engineers trying to convince the naval engineers that the LNG tanker wasn't a great problem, while the latter assured the cryogenics group that they "didn't have to be so particular."

The cryogenics group maintained considerable contact with former colleagues at Convair. "Whenever we had a problem we just called up Convair, and they helped solve it. It was a joint effort." Among the services the sister division rendered (in addition to those already cited) were judgments on acceptability of welding of the aluminum spheres, and analysis and design studies for the tank production line. (Convair's experience in designing tools to assemble large components for the space shuttle and DC-10 fuselages was cited as extremely relevant to these services.) The last task grew out of problems with Pittsburgh Des Moines Steel (PDM), to whom General Dynamics had subcontracted the fabrication of the 120-foot-diameter spherical tanks. Before the first set of tanks was fabricated, PDM defaulted on its contract. In December 1974, General Dynamics purchased the site of PDM tank construction and took over production of the spheres.

Since 1972, General Dynamics has received orders from Energy Transportation Corporation for five additional 125,000 cubic meter LNG tankers. Because these ships will enter the Indonesia-Japan route, they are not as vulnerable to U.S. regulatory controls. Nevertheless, all are being built to the same fundamental design specifications as the first three. No attempt has or is likely to be made to introduce more advanced (aerospace) technology. According to a Quincy Shipyard executive, this heeds the shipowner's desire for standardization and the shipbuilder's reluctance to try technology that has not "proven itself totally reliable in the context of commercial usage."
first three General Dynamics tankers were ordered faces an uncertain fate. The importing utility began filing applications for approval early in 1973. But the FPC failed to rule before the contract deadline (1975), and the Algerian government-owned supplier "cancelled" the contract. Renegotiation, which is expected to result in an increase in the price of the gas of up to 300 percent, and reapplication for approval are now underway.

"Inhibitors" and "Promoters" in the Process of Technology Transfer

The LNG tanker case study amply illustrates some of the major influences in the transfer of technology to secondary uses. It encompasses major "inhibitors" and primary "promoters," which are common to other cases as well.

By far the most important constraints to transferring advanced aerospace technology to LNG tankers are the considerable financial and safety risks. The huge capital investments required for tankers and shoreside complements to a natural gas import project have far-reaching implications for technological innovation in the industry. Shipowner, shipbuilder, and ship lessee alike are understandably reluctant to jeopardize major outlays and potential profits by introducing technology that may be unpredictable or cost-ineffective in its new environment.

Sophisticated aerospace technology is frequently more expensive than conventional technology. Aerospace technology might afford some improvements over items currently in use, but if it does not provide improved reliability or other benefits to outweigh the increase in price, transfer is inhibited. Internal superinsulations, new metal alloys, and fibers were cases in point. The leader of General Dynamics' cryogenics group put it succinctly: "If it were economical, we'd gladly use it." 25

Another critical constraint to transferring technology is the institutional net that engulfs any LNG tanker destined for U.S. trade. The list of federal, state, and local regulatory agencies involved is long; it has been only partially detailed above. The safety issue is of direct concern to most of those involved in approving an LNG project. 26 Most participants take the conservative approach. For example, the U.S. Coast Guard, which sets standards and certifies the safety of any U.S. flagship, published standards for LNG tankers in 1965 based on the contemporary state of the art. Updated after 10 years, the standards still do not reflect many of the technological advances made by the aerospace sector in the interim. 27

For its part, the FPC not only regulates economic aspects of gas import projects but, in approving terminal facilities, must also meet the requirements of the Environmental Protection Act. For the first major U.S. LNG import project, the FPC took 49 months to render the necessary approvals. In the past few years, procedures attendant upon filings, hearings, amendments, and approval of environmental impact statements have increased, and they now constitute one of the major hurdles in the entire process. This is at least partly attributable to the 1973 explosion of a Staten Island LNG storage tank, which killed about 40 people. 28 The result of the accident has been the proliferation of organizations involved; intensification of their conservatism; and reintroduction of a plethora of social, environmental, and political considerations.

Legal arguments at FPC hearings now focus primarily on selecting sites for terminal facilities to which foreign LNG can be delivered. Emphasis is often placed on identifying "excessive risks" involved in such occurrences as a sinking or major collision involving an LNG tanker in a busy harbor. (Pollution does not figure prominently in the issues.) Even the Coast Guard's assurances of the safety of the ship, a letter-of-compliance program for all ships entering U.S. harbors, contingency plans for special navigational aids, and the relative safety of LNG tankers as compared to oil tankers in the respects of fire, pollution, and grounding have not blunted opposition to the terminals—neither have appeals on the basis of national energy needs. 29

Illustrative of this maze of bureaucratic and social barriers are the two-year old hearings for approval of several LNG tanks in the Staten Island area for a large import project to New York harbor. Through mid-1975 the hearings attracted over 80 legal participants and interners and generated 50 to 60 volumes of pleadings. There was no end in sight and no clear answer even to the status of the procedures. 30 In addition, fallout from the case was felt in almost every other LNG project where approvals were pending. Those projects where approvals had already been granted were being reopened. 31 Of the latter, one was reopened because of an increase in price imposed by the Algerians.

The outlook for importing LNG and ordering LNG tankers is unquestionably affected by these regulatory hassles. One executive commented after two years of awaiting FPC approvals for a large import project:
"We do not see how we can hold the project together much longer." 32 Another observed that delays and uncertainties in regulatory procedures present "immeasurable risks" that have already left behind a "series of abortive projects." 33 In spite of this gloomy picture, however, some of those fighting the battle against LNG terminals admit that the big economic interests at stake and the country's energy requirements will prevail; LNG import projects will probably go forward eventually; and the most they can hope for is more stringent safety regulations, a strong national policy on siting,34 and substitution of other fuels for natural gas.

The economics of importing LNG and the inconsistencies in the national energy policy (or lack thereof) are also major hurdles for tankers designed to carry only that fuel. As noted above, FPC controls on natural gas have kept both the price and the supply of domestic natural gas down. At the wellhead, natural gas was priced at the end of 1975 at about 50 cents per thousand cubic feet and was delivered at about $2.25-$2.75, depending on the distance from the source of supply. Algerian gas had risen to about $1.20-$1.40 per thousand cubic feet, which handling, shipping, conversion, reconversion, and terminal costs brought to between $3.00—$3.50 (in the best case of a fully operational project). Import LNG was therefore marginally competitive with domestic gas.35 The economics of importing LNG, however, are subject to international politics, unpredictable operating costs, relative prices of competitive fuels, and—very significantly—the potential for increasing use of other energy sources. The widening gap between domestic demand and supply of natural gas is a strong incentive for U.S. energy interests to pursue efforts to import LNG. But an adverse change in any of the factors identified above could seriously alter the outlook for large-scale LNG import projects.

Fundamental differences between the aerospace and marine environments also impede transfer of technology between the two. The shipbuilding industry has long been conservative. In its highly competitive world marketplace, cost is a big factor, profit margins are small, and skilled labor is expensive. Basic technology, with some exceptions, has been largely the same for decades, providing assurance of rugged, long-lived equipment.

By contrast, the aerospace environment is fast moving and progressive. Cost has historically been a secondary consideration. (While this is changing in the competitive arena of commercial aircraft, it was char-
acteristic of the manned space program and of many of the military rocket or missile and aircraft programs.) The aerospace environment is often unforgiving; it demands light weight, miniaturization, and high reliability for a relatively short life. These special demands have been met with research and development programs and extensive quality control and pretesting (all of which are very costly). At the edge of new developments and advanced technology, the aerospace industry has been prone to improve and innovate rapidly (allegedly sometimes to the extent of incorporating technical advances for their own sake). The effect of these fundamental differences has been to make transfer of aerospace technology to the marine environment difficult.

In spite of the above constraints, there were several factors that served to stimulate transfer of aerospace technology to the LNG tanker. Most significantly, by far, was the use of engineers who effected transfer. The indispensable role of these promoters was clearly evident in the LNG tanker case. Whether forced or merely nudged by corporate management, when the aerospace engineers were transferred to the shipbuilding division, they took their technological bags with them. They drew on their aerospace experience and assistance. The successful transfer of technology must be attributed in the first instance to the transfer of technologists. The essence of most of the technology transferred—analytical methods and engineering approaches—resided in the individuals, not in the devices.

Other major influences that promoted the transfer of aerospace technology to LNG tankers were the growing national need for energy; the shared interest in cryogenic technology between the aerospace and the LNG tanker industries; federal government interest in stimulating development of U.S. LNG tankers and, coincidentally, in utilizing cryogenic technology developed for the space program; and the relationship between Quincy Shipyard and a large aerospace conglomerate.

Conclusion

The successes in transferring aerospace technology to the LNG tanker are testimony to the decisive role that the technologist plays. They also reflect the importance to application in other environments of many aerospace advances in technology. The need for additional energy resources, the influence of financial
interests, and the momentum of tanker production programs may prove effective promoters of future transfers to LNG shipbuilding.

At the same time, a poor prognosis for future transfers may prevail: The price of foreign natural gas has soared; national priorities have shifted from clean energy to self-sufficiency; MarAd has virtually eliminated its entire cryogenic support program; indicators in the tanker industry are bearing out predictions of a decline in demand for LNG tankers by 1990; the widespread side effects of the 1973 Staten Island explosion have discouraged potential gas importers; and the FPC has not yet (1977) given final approval to a single import project for which any of the 16 LNG tankers under construction in the United States are designated.

Whatever the future of the LNG tanker, the experience gained in this case provides useful lessons for understanding and driving the technology transfer process. Successful transfer, for example, clearly depends to a large degree on the existence and support of several effective promoters: innovative and dynamic people; strong financial support; identifiable needs; relevant technological solutions; cooperation between key institutions and individuals; tolerance of risk; and demanding specifications of performance.

There are several significant factors that consistently inhibit transfer: cost, obstructive policies, incompatible environments, political influences, and inappropriate technology are a few. Understanding these factors may well lead to the critical guidelines necessary for achieving successful transfer of technology.

Notes

2. Ibid.
6. Ibid.
7. Interview, Philip L. Ross, assistant to the general manager, Market Development, General Dynamics, Quincy Shipbuilding Division, 18 October 1974, 11 and 20 August 1975, and letter with enclosed comments, 29 April 1975.
8. "Benefits Briefing Notebook" prepared by the Denver Research Institute for NASA Technology Utilization Office, September 1974 (review draft); Denver Research Institute, Cryogenics, A Technology Transfer Profile, Applications of Aerospace Technology in Industry (December 1971), prepared for NASA; Denver Research Institute, A Case Study in Technology Utilization: Fracture Mechanics (May 1972), prepared for Technology Utilization Office of NASA; interview, Rolf D. Glasfeld, chief development engineer, General Dynamics, Quincy Shipbuilding Division, 18 October 1974, and review comments, 29 April 1975; interview, Ross Buck, cryogenics engineer, General Dynamics, Quincy Shipbuilding Division (formerly with Convair Division), 18 October 1974; telephone interview, Alan Schuler, manager Cryogenics Engineering, Quincy Shipbuilding Division, General Dynamics (formerly with Convair Division), 11 and 18 August 1975; Martin Marietta, "Capillary Internal Insulation System" (technical data report, March 1973); Rockwell International, Space Division, Wet Wall Insulation System for LNG Tankers (June 1973); interview, Richard Breed, Materials Division, National Bureau of Standards, Cryogenics Division, Boulder, Colorado, 19 September 1974.
10. Department of Commerce, LNG Tank Designs; du Barry and Schwendtner; Analysis of LNG Marine Transportation.
11. Schuler interview.
13. Schuler interview.
14. None of the other LNG shipbuilders, i.e., Avondale, Newport News, and Sun Shipbuilding and Dry Dock, had direct aero-space connections.
15. Unless otherwise noted, all information directly related to the General Dynamics (Quincy Division) LNG tanker program was provided through the previously cited personal interviews and telephone conversations with Ross, Glasfeld, Buck, Schuler, and through interview, Edward Heineman, vice president of Engineering and Program Development, General Dynamics (retired), 25 October 1974.
16. Nine U.S. LNG tankers had been subsidized through 1975, the last three at the rate of 16.5 percent.
18. Andrew E. Gibson and Marvin Pitkin, Maritime Administration, "Developments in LNG Transportation in the U.S.,” paper delivered to the Third International Conference and Exhibition of Li-
quid Natural Gas, 26-28 September 1972, Washington, D.C.


20. Not entirely for the LNG tankers but partly to reduce the labor component in the shipyard generally.


22. The difficulty and need to "force" interdivisional transfer was also noted in the cases of Boeing, Westinghouse, and Philco-Ford.

23. Schuler interview.

24. Ross interview.

25. Schuler interview.

26. The process of gaining approval for an LNG import project is focused primarily on shoreside facilities, but because the tanker's ability to operate is clearly a function of their approval, the entire process and all its participants have as great an impact on any tanker in U.S. trade as Coast Guard certification of the tanker design itself.


28. The explosion occurred during maintenance of an empty tank (which had been used to store LNG briefly in 1971-1972) and was attributed to faulty construction of the insulation.


30. Terris interview.


32. Caramero, "Energy, Money and Ships.”

33. Ross interview.

34. A bill pending before Congress required the Commandant of the Coast Guard to select "appropriate" sites for LNG storage terminals (as opposed to current selection of such sites by the companies involved), HR 4440, bill introduced to House of Representatives, 6 March 1975, by Congressman John M. Murphy (D-NY).

The Delphi Method of Technological Forecasting

J. Gordon Milliken

EDITOR'S COMMENT

Our third study describes a social scientific invention. The method called "Delphi" was created to predict developments in weaponry after World War II, and its close alliance to this technology has motivated us to include it here. Nevertheless, Delphi is removed from the aerospace industry one step further than the technology discussed in the previous cases. Indeed, while the method was developed at the Rand Corporation—a military and aerospace industrial "think tank"—it has been used increasingly in industries that have no interest in aerospace hardware or methods. Delphi is a means of prediction by surveying opinion of a panel of experts, to create a collective judgment. Its defining characteristic is a mechanism of "feedback" by which diverse expert opinions are induced to converge toward a consensus.

J. Gordon Milliken, the author of this study of Delphi, is a management scientist at Denver Research Institute and headed a team of researchers that produced nine studies for the National Air and Space Museum. This study and the two that follow were extracted from their unpublished report of 1975, Aerospace Contributions to Management. He has exhaustively searched the literature of Delphi, which is immense, and he has conducted interviews with founders and users of the method. The major portion of his study is devoted to a list of many uses to which Delphi has been put, but his most interesting research is embodied in two sections: "A Study of How Delphi is Used" and "The Validity of Delphi."

In the first of these, Milliken has chosen a Delphic study that preceded a conference on education of management at the University of Colorado. He has described the method of questioning, the iteration and feedback, and the judgment of the participants that their use of Delphi was successful. He notes that the discussion of the method in the conference was itself a mechanism of diffusion of knowledge of Delphi.

In the second of these, Milliken's research suggests that the history of Delphi is like the history of some new methods in the exact sciences. A major synthetic accomplishment—the theory of ordinary differential equations, for example—is followed by widespread use and modification of the new method. Soon, however, a critical reaction sets in, for despite its success, the method is built on uncertain foundations. The search for proofs of existence, uniqueness, and reproducibility constitutes a phase of growing rigor, and in Delphi it takes us to the present. We find in Milliken's documentation that many have judged the method to have been widely misused. But the range of applications expands, and the advocates of Delphi predict more frequent use.

Planners in education and government will no doubt use Delphi to reinforce their preliminary judgments, but corporations may have less use for it. There are at least two reasons for this. First, a chief executive or board of directors may decide the course of the firm, expecting that it will change also the environment in which it conducts business. Delphi is unlikely to anticipate such a change. A company that controls a large portion of the supply to the market in which it competes changes the behavior of the entire market when it changes its level of production. The monopolistic company can quickly render the perception of a Delphi panel invalid, because the panel, even if it sits within the company, is not privy in advance to major policy decisions. Delphi smooths out discontinuities, discounts radical changes, and thus is insensitive to the important effects of corporate policy on economic and technological development. Second, Delphi imposes an objective scale on highly subjective, often qualified statements. Yet a corporate executive who solicits expert opinion wants to weigh the ramifications of the issue he or she is about to decide. Delphi gives him less information than full expert opinions, and it usurps his responsibility to make a decision that may determine great profit or loss.

Even in industry, however, routine decisions in planning can come from Delphi. With the essential addition of a feedback mechanism, Delphi is a significant alternative to simple polling. At the cost of time and of money it provides a new kind of information, a consensus of sorts, which may be carefully used to advantage.

Delphi is a method for acquiring collective predictions of events from many informed judges. When lack of objective data rules out conventional technological forecasting by extrapolation, for example, Delphi is used to develop a consensus of experts. Where an adequate consensus cannot be reached, Delphi can at least reveal polarization of opinions between two factions. From its early use at Rand and in other research groups working for the U.S. Air Force, Delphi has spread to government agencies, corporations, and academic institutions. The Delphi method of technological forecasting is one of very few techniques for planning which is new, not the product of adaptation or improvement of a prior method.

Delphi entails the repeated interrogation of respondents (usually chosen for their expertise) regarding their expectations or understandings. They are queried separately, to avoid biases of authority. The
median or distribution of responses is then furnished to the respondents, who may stand by their judgment or alter it. In some cases, especially for deviant opinions, statements of justification are sought, and these also are furnished to the respondents to further stimulate original judgments. Finally, the estimates are stated in the form of a consensus judgment.

Norman Dalkey, a coinventor with Olaf Helmer of the Delphi technique, describes the two basic assumptions that underlie Delphi inquiries:

(a) In situations of uncertainty (incomplete information or inadequate theories) expert judgment can be used as a surrogate for direct knowledge. I sometimes call this the "one head is better than none" rule.

(b) In a wide variety of situations of uncertainty, a group judgment (amalgamating the judgments of a group of experts) is preferable to the judgment of a typical member of the group, the "n heads are better than one" rule.

The use of Delphi avoids some common problems of decisionmaking in a committee or special task force. The technique eliminates judgments based on "he who shouts the loudest," and it weakens inhibitions sometimes held by group members of lesser rank or reputation. Further, it allows members of the group to abandon earlier judgments that are later seen to be erroneous, without the embarrassment of reversing publicly held opinions. This is indicated by the tendency of opinion to converge after several rounds of anonymous response and feedback. Delphi also tends to avoid the problem, encountered in group discussions, of confusing the main issue with irrelevant argument among members of the group. It also controls group pressure, which strongly influences members of a group to compromise their sincere judgments.

Norman Dalkey points out that Delphi procedures have been designed to minimize the undesirable effects of group interaction described above:

The [Delphi] procedure has three distinctive characteristics:

- Anonymity
- Controlled feedback
- Statistical "group response"

Anonymity is a device to reduce the effect of the socially dominant individual. It is maintained by eliciting separate and private answers to prepared questions. Ordinarily, the procedure is carried out by written questionnaire; on-line computers have been used for some exercises. All other interaction between respondents is through formal communication channels controlled by experimenters.

Controlled feedback is a device to reduce noise (among other things). A Delphi exercise will usually consist of several iterations where the results of the previous iteration are "fed back" to the respondents, normally in summarized form.

As a representative of the group opinion, some form of statistical index is reported. For cases where the group task is to estimate a numerical quantity, the median of individual estimates has turned out to be the most useful index tried to date. Thus, there is no particular attempt to arrive at unanimity among the respondents, and a spread of opinions on the final round is the normal outcome. This is a further device to reduce group pressure toward conformity.

Some understanding of the effect of iteration can be obtained from a comparison of the graphs in Figure 1, taken from Dalkey's *The Delphi Method: An Experimental Study of Group Opinion*. Figure 1 (top) shows that the distribution of first-round answers to numerical questions that have specific answers approximates a log normal curve. Figure 1 (bottom), taken after one round of feedback and a new response, shows that the answers have shifted dramatically toward the mean, indicating a convergence of answers toward the (average) response of the group.

Dalkey summarizes the Delphi methodology:

A typical exercise is initiated by a questionnaire which requests estimates of a set of numerical quantities, e.g., dates at which technological possibilities will be realized, or probabilities of realization by given dates, levels of performance, and the like. The results of the first round will be summarized, e.g., as the median and inter-
quartile range of the responses, and fed back with a request to revise the
first estimates where appropriate. On succeeding rounds, those
individuals whose answers deviate markedly from the median (e.g.,
outside the inter-quartile range) are requested to justify their esti­
mates. These justifications are summarized, fed back, and counter-
arguments elicited. The counter-arguments are in turn fed back and
additional reappraisals collected. This basic pattern has, of course,
many possible variants, only a few of which have been tried.1

Appendix 1 is the set of typical instructions for a Delphi experiment using questions for which the
answers are known to the experimenters.8 Experiments
using such almanac-type questions as “What was the
number of telephones in Africa in 1962?” or “How
many married students were enrolled in high school in
the US in 1965?” can test the accuracy and con­
vergence of Delphi. Where confirmation is possible, experi­
menters have found that opinions tend to con­
vergence during the experiment, and generally the me­
dian response moves in the direction of the true
answer. Where confirmation is not possible, one can
say only that opinions do converge during the
exercise.9

Appendix 2 contains examples of the almanac-style
questions used by Norman Dalkey and his Rand col­
leagues in Delphi experiments with students of the
University of California at Los Angeles. The size of
group error in the responses is also shown.

One additional feature of present Delphi procedures
should be mentioned. Respondents are usually re­
quested to rate their self-confidence for each response.
Several different kinds of self-ratings have been tried:ranking the questions in the order of the respondent’s
judgment of his competence to answer them and esti­
mating self-confidence with respect to some reference
group. In general, there has been no significant cor­
relation discovered between self-ratings and “indi­
vidual” performance for estimates that can be con­
firmed. It has usually been possible, however, to select
a subgroup of relatively more confident individuals
whose performance has been slightly, but consistently,
better than the group as a whole. In one very thorough
study, the improvement was obtained only by combin­
ing two self-rating indices—the ranking of questions
and absolute estimates of confidence.10

Much work with Delphi has been experimental, but
the results of the experiments show considerable prom­
ise for its regular use. Dalkey has found in experiments
with college groups that the group opinion improves
after Delphi iteration, whereas the consensus becomes
less accurate if group discussion is allowed.11

History of Delphi

Technological prophecy has existed throughout his­
tory.12 ‘Technological forecasting, a less intuitive and
more disciplined effort, was given major impetus dur­
ing World War II as the U.S. Army Air Force began
planning for the future. In 1944, Theodore von Kár­
mán and others published Toward New Horizons,
which related expected technological growth to the
future Air Force.

At the end of World War II, many persons in gov­
ernment were convinced that it was important to con­
tinue the collaboration between scientists and the
military established during the war. Civilian advisors
to the Secretary of War proposed a new kind of orga­
nization to serve the national security and the public
interest. The Air Force let a research contract to
Douglas Aircraft Company of Santa Monica for Proj­
ect “RAND.” 13 In 1948, it was decided to separate
RAND from Douglas. With Ford Foundation funding,
and a distinguished nongovernmental board of trust­
ees, the Rand Corporation was formed “to further and
promote scientific, educational, and charitable pur­
poses, all for the public welfare and security of the
United States of America.” Its first and principal con­
tract, for the conduct of Air Force Project RAND,
called for “a program of study and research on the
broad subject of intercontinental warfare, other than
surface, with the object of recommending to the Army
Air Forces preferred techniques and instrumentalities
for this purpose.” 14 The first RAND project, com­
pleted and reported in May 1946, was a study of the
feasibility and utility of an earth-circling space ship.

In the early years of Rand, experiments were con­
ducted on the techniques of technological forecasting.
Norman Dalkey mentions an intermittent series of
studies on using group information effectively: “The
early studies were concerned mainly with improving
the statistical treatment of individual opinions.” 15 A
key event in the development of forecasting techniques
occurred in 1950 when a group of statisticians did a
study to determine the results of pooling horse-race
handicapping opinions. Though one would lose after
betting on a number of horse races, one would not lose
as much when following the opinions of the pooled
handicappers as when one followed the advice of one
handicapper. Because of the “negative” results (that
the better would lose), the significance of this study
was not recognized immediately, and it was never pub­
lished. Another extensive study of short-range predic­
tions16 had indicated that some properties of individ­
ual estimates (precision, definiteness) could be used to correct the accuracy of short-term predictions and that background information (as measured by a standard achievement test) had a small but significant influence on the accuracy of predictions. Both of these effects, however, were fairly washed out by combining estimates into a group prediction.

The importance of these results became apparent as Rand scientists tried to determine the probability of general war in an evaluation of future enemy weapons for the Air Force. Early in their research it became clear that technological developments should be predicted, and to this end they decided to experiment with intuitive judgments of physical and social scientists.

Faced with a U.S. Air Force request for a classified study of bombing requirements, and needing technological forecasts, Norman Dalkey and Olaf Helmer in 1951 built upon this early work and conducted the first true Delphi study. Their experiment was from the viewpoint of a Soviet strategic planner—to apply expert opinion to select an optimal group of U.S. targets and to estimate the number of atomic bombs required to reduce the munitions production by a required amount. Dalkey and Helmer’s important innovation was the introduction of iteration with controlled feedback. The set of procedures that evolved from this work has received the name “Delphi”—a misleading appellation in Dalkey’s opinion, since his colleagues and he believe that there is little that is oracular about the methods.

Dalkey commented that all of the work done on Delphi at Rand from 1952 to 1962 was purely aerospace activity; some of the studies are included in Rand’s 1974 selected bibliography. The Delphi procedures received a great boost in general interest in 1964 with the publication of Gordon and Helmer’s study of forecasting technological events. This study produced predictions as much as 50 years into the future, dealing with six areas: scientific breakthroughs, population growth, automation, space progress, probability and prevention of war, and future weapons systems. The study happened to coincide with a surge of interest in long-range forecasting, with an attendant interest in the systematic use of expert opinion.

Throughout the 1960s, Delphi was used predominantly in aerospace industry and the military. The U.S. Air Force funded Rand’s continuing research and conducted some experiments of its own. The Air Force Systems Command and Office of Scientific Research conducted pilot studies of social and technological forecasts. The technique was employed in at least two doctoral dissertations in the mid-1960s, and its use in military and commercial applications became more extensive during the late 1960s.

There were several important nonaerospace applications, however. In the late 1960s, the Institute for the Future (IFF) conducted a series of studies for the state of Connecticut, which were designed to examine the state’s future and to aid long-range planning for Connecticut. Related work was conducted by IFF for the Electric Power Research Institute.

In 1969 Dalkey stated in a Rand memorandum, “At present, it is difficult to obtain a clear picture of how widespread the applications are; but a crude guess would put the number of studies recently completed, underway, or in the planning stages at well over a hundred.”

Applications

In a review of Delphi, Olaf Helmer describes the proliferation of uses of the technique:

While its principal area of application has remained that of technological forecasting, it has been used in many other contexts in which judgmental information is indispensable. These include normative forecasts; the ascertainment of values and preferences; estimates concerning the quality of life; simulated and real decision-making; and what may be called “inventive planning,” by which is meant the identification (including invention) of potential measures that might be taken to deal with a given problem situation and the assessment of such proposed measures with regard to their feasibility, desirability, and effectiveness.

There are two basic areas of application of Delphi, according to Helmer, one of which has to do with inputs into research, the other with the utilization of research output: The first such application consists in the employment of Delphi surveys to provide judgmental input data for use in studies in the social-science area, in cases where hard data are unavailable or too costly to obtain. For instance, in a study of socioeconomic strategies for a developing country, reliance on judgmental information supplied by area specialists may be an adequate substitute for hard, but nonexistent data. The other major application of Delphi, of which numerous examples already exist, is to the process of gathering of expert opinions among the nationwide “advice community” on which governmental decision-makers frequently rely. In this mode of application, Delphi can be of considerable utility, both by systematizing the process and by lending greater objectivity to its “adversary” aspects.

TRW, Inc., a consolidation of the aerospace firm of Ramo Woolridge with the conventional manufacturer
Thompson Products, Inc., has been an early user of technological forecasting "that can provide management with the distance vision it now requires to do its job . . . to help management improve its decision-making processes by providing immediate information on probable and significant future trends." The primary applications of technological forecasting at TRW were to plan strategies for research and development and to identify opportunities to develop new products. Harper North and Donald Pyke of TRW commented:

We decided to employ a modification of the Delphi method . . . developed and used by the Rand Corporation. This method seeks to take full advantage of the "committee" approach to forecasting, while avoiding some of the disadvantages of the typical brainstorming session.

For the most part, our initial attempt to generate a long-range forecast of the technological future was a test of the feasibility of using the Delphi method in an industrial environment. It consisted of an experimental survey, finally completed in June 1966, which led to a 50-page proprietary document titled, "A probe of TRW's future: the next 20 years." This document listed some 401 technical events, sorted into 15 categories, which a single panel of 27 experts specializing in a broad spectrum of technologies felt would occur by 1986 and which they believed would have significant impact on the company's products, services, and processes. This experiment later became known as Probe I. Before launching a second stage, Probe II, the 15 categories of events were refined to focus more closely on our current interests.

The TRW experience with Delphi proved not to be as successful as North and Pyke expected in 1969. Wayne Boucher, a former Rand colleague of Helmer and Dalkey's and now with The Futures Group, stated in an interview that TRW's Probe work was not put to use as a basis for making decisions on TRW's future programs, "despite the support of Ramo and others who committed themselves to making Probe a permanent part of their future. The problem was data overload. Yet Delphi did have a great impact on shaping the conceptual future of technology—and Probe has apparently served from time to time as a guide to such thinking."

Norman Dalkey stated in an interview:

In the area of technological forecasting, TRW Systems used Delphi for informational purposes only. They began with a list of 1,800 potential technological events and asked the panel to predict when they would happen, their feasibility for development, and their significance to TRW. They classified events into 20 areas and then predicted the probability of each event existing within one of several time periods. TRW planners discovered that they needed to develop certain intermediate technologies to get to the final point. They found that intermediate technologies like laser optics were more interesting than the final technologies, and they are now putting development money into certain of the intermediate technologies.

Besides TRW, Dalkey noted, the two aerospace firms of Boeing and Northrop have used Delphi for technological forecasting.

Boucher noted that The Futures Group has used Delphi in numerous fields: to forecast the future of the photographic industry, biological processes, the Japanese economy, beverages, food technology, various energy sources, psychotropic (mind-altering) drugs, communications equipment, and other subjects. In the study of communications equipment, The Futures Group first used a variation of Delphi—interview Delphi—to design physical equipment to test its acceptability by users. Managers of telephone exchanges were asked to forecast design features desired on a switchboard. The interview Delphi results were used as a basis for a multimillion dollar decision. Because of the considerable financial impact of the decision, it was made only after the client had spent several months testing, and failing to refute, the findings of The Futures Group. Interview Delphi has since been used by The Futures Group in many other studies. According to Boucher, its advantage over the questionnaire technique is so clear that it has become the preferred approach to Delphi at The Futures Group. Other organizations also are now using it.

Delphi has been adapted to such business-related matters as the impact of increased leisure time on industrial product lines. Norman Dalkey estimated in a 1974 interview that during the past five years about 1500 Delphi studies have been undertaken. Most of the industrial studies, however, have not led to decisions to act. They seem to be of interest to top management, but often administrators are unsure of what to do with the results or are unwilling to commit resources to implement them. Dalkey did not attribute this lack of impact on industrial policy to any basic flaw in the Delphi method or to a lack of managerial confidence in it. Instead, he felt that there was a considerable distance between the subject of the Delphi exercise and the subject matter that would be used for a policy decision. Dalkey hopes that external studies will soon give way to panels within companies.

In a recent use of the technique, which is indicative of Delphi results substituting for data, the California Air Resources Board surveyed a panel of doctors to estimate the doses of pollutants that would have certain effects on incremental percentages of the population. This, Dalkey explained, is the most straightforward application of Delphi, because it is specific.

On the other hand, government and industry may use Delphi to identify the goals of their organizations.
Many of these are done in-house as part of long-range planning, and they are general. In between the two extremes lies the use of Delphi for technological forecasting. According to Dalkey, this most subjective use of Delphi differs from the more objective applications in that it is rare that one initially asks the right questions. A few iterations are necessary solely to define the questions. Dalkey gave us the example of one organization that questioned 30 executives at the level of division chief or above to define the five most important goals of the organization. The first questionnaire brought 127 different responses. Cluster analysis reduced the variety of responses to a workable number. This example demonstrates two problems inherent in applying Delphi to subjective topics. First, questionnaires must deal with limited areas in order to illuminate relations among many variables. The second problem lies in determining what is worth forecasting. In the more subjective areas, those who make decisions are less likely to use forecasts.

The Corning Glass Company uses a derivative form of Delphi in its shorter range planning for developing new products. The planning division asks its engineers what new products will be possible in the coming year and asks management how much money will be available for new product development. With this information, planners develop alternative yearly “packages” or combinations of new products that could be developed within the funding limitations. Concurrently, Corning develops a set of objectives for their share of the market, long-run profits, and other company goals. A working panel of 12 members then determines what effect each alternative will have on the company and on its goals. On the basis of this information, a decision is made as to which packages will be pursued. Two articles by John C. Chambers and others at Corning describe this method of planning. Dalkey stated that the Corning process is almost continuous, but he emphasized that once the objectives of the company are established, they are infrequently modified.

Monsanto Chemical Company, a firm that has pioneered in the use of futures research for deciding practical policy, has applied the Delphi method to generate data for its top management to plan for the long range. Monsanto also uses the cross-impact analysis developed by Ted Gordon of The Futures Group, which takes into account the effect of one event on the probability of other events. (Delphi is used to make the probability estimates necessary for cross-impact analysis.) The technique also relates the effect of selected events to Monsanto’s goals. The case of Monsanto is one of the few in which one can document the use of Delphi to arrive at decisions on policy.

The largest Delphi study yet attempted was done by the Japan Techno-Economics Society. A panel of 4000 engineers, scientists, and intellectual leaders in Japan was polled on 620 subjects—to forecast for the Japanese government future scientific and technological developments. It was the first major attempt on the part of an organization of government to utilize Delphi in its long-range planning. Unfortunately, the content was sufficiently remote from policy issues of interest to the Japanese government and the study was so extensive that the government had great difficulty using it.

Dalkey noted that the Air Force had made little use of the technique, whereas the Army and Navy have used it more extensively. The CIA was interested in using it about three years ago but, to Dalkey’s knowledge, it has never done so extensively.

Dalkey remarked that the largest number of applications of Delphi occurred in the field of education. For example, Miami-Dade Community College used Delphi to set the objectives of the school and to measure the effectiveness of efforts to reach them.

Abt Associates is performing research in drug abuse. The study, sponsored by the National Institutes of Health, uses Delphi methods to evaluate the goals of several programs. There is also an exploratory survey being done by the U.S. Public Health Service to review objectives of research sponsored by the service.

Rand also has applied Delphi to prevention and treatment of drug abuse. Other Rand applications include population estimates for cities, forecasting energy demand, intercity transportation, educational innovation, and cable television.

An especially promising application of Delphi is in determining value judgments of groups, notably in judging the quality of life. In a 1968 paper, Dalkey reviewed several “armchair” surveys of human happiness, satisfaction, and mental health. He then proposed a research effort based on Delphi:

The basic idea is quite straightforward, namely, to prepare a comprehensive set of scales relevant to the quality of life; let a large, representative sample of Americans rate themselves on these scales via confidential interview; and employ factor analysis to summarize the interrelations between the ratings. With any luck at all, many of the factors derived in the analysis would be interpretable and could replace the armchair lists with something more solid. . . .

Since one expectation would be that the results of such a study would be relevant to policy in the urban and domestic areas, several blocks of scales should be allocated to issues directly involved in these, e.g., amount of time spent in parks and places of public recreation, satisfaction with neighborhood, amount of income from welfare payments, and so on.
By 1970 Dalkey and others had completed several Delphi studies and had developed a model for the quality of life (QOL) "that has been useful in suggesting lines of investigation and in interpreting data. The model includes a set of general characteristics or qualities of the stream of events occurring to an individual that largely determine his sense of well-being." With the model "one can estimate the potential level, but not the precise pattern, of QOL at a given time." The model was used to examine the panel's satisfaction with different modes of transportation. This examination guided the Department of Transportation in setting policy, thus illustrating the usefulness of the method "to those interested in the impacts of the variety of domestic public programs—education, health, housing, transportation, welfare and the like—upon the quality of life." 46

In a 1973 study, Dalkey improved the QOL procedure further. Respondents were asked to estimate statistical weights for those factors that they judged to be important in determining the quality of life of an individual. Cluster analysis, a statistical technique for grouping data, was used to aggregate the long list of factors that were elicited. Relative importance of the factors was measured by a Delphi exercise and by a self-rating of overall quality of life. From the study Dalkey concluded:

[T]he sense of well-being enjoyed by an individual depends upon the extent to which his experiences exemplify several basic characteristics. Inherent in this view is the existence of trade-offs among these characteristics; two different individuals can enjoy about the same level of quality of life with highly different patterns of experiential rewards. One can be comfortable, receiving a great deal of love and affection, and living a routine existence; the other can be living an exciting life, with a high sense of achievement, and lonely, and each report about the same overall level of well-being.47

Bell Canada, a communications firm serving Ontario and Quebec, has used Delphi extensively for business planning. The firm has explored future technological developments in education (e.g., computerized library systems, computer-aided instruction systems, and visual display systems such as instant retrieval television), which suggest a market for Bell Canada. Bell Canada conducted similar Delphi exercises in medicine (e.g., multiphasic screening, computer-assisted diagnosis, remote physiological monitoring), in business information processing (e.g., management information systems, mini and small computers, terminals and data processing), and in home telecommunications services.48

Delphi has been applied to the future of pharmaceuticals—conducted by Smith, Kline, and French and by three other pharmaceutical manufacturers.50 Two Delphi studies dealing with environmental topics are notable. In 1972 the program of Research Applied to National Needs of the National Science Foundation convened a workshop on energy and the environment to provide a background report for the Senate Interior and Insular Affairs Committee. Its product, "Growth Rate of Energy Demand," was published as a Rand document.51 This report focused on the need for energy conservation and recommended policies ranging from education and voluntary measures to rationing and bans on consumption of energy.

The Environmental Protection Agency used Delphi as one of six techniques for estimating the damages caused by air pollution in the United States. The report commented:

Given the dearth of air pollution dose-response information, it is possible that the delphi method, which relies on subjective opinion rather than objective data, will be used in a more significant way. It seems obvious that where substantial information is missing, the pooled judgments of experts could provide useful information to the decisionmaker on the general magnitude of damages over a range of pollution levels.52

Transferring Delphi

Transfer of Delphi from its early use on military problems to more general technological forecasting has been accomplished largely in two ways: first, by experimenters at Rand and elsewhere who have found it adaptable to many other areas of interest to society; and second, through published accounts of the method, which have been extensive. Dalkey credits the success of the Delphi technique to its use of firm and systematic procedures for the first time in forecasting by judgment. The simplicity of the procedures and the many obvious applications of the technique make it easy to apply. Although it has been described here as an aerospace-related technique because of its origins, there is nothing that intrinsically limits its applicability to air and space.

Many applications of Delphi have been made by individuals who read or heard about it and proceeded from written instructions in the literature. Some face-to-face contact with the original developers has occurred at professional meetings and in personal visits. But in the main, all that is necessary to employ the technique is a publication or two from the Rand Corporation or the "methodology" section of a previous study.

Its flexibility and ease of application do not, however, assure that Delphi always can be used successful-
ly. As proponents and critics agree, there are many cases where the Delphi technique has been poorly handled and improperly applied.

**A Study of How Delphi Is Used**

In 1973, the College of Business and Administration of the University of Colorado hosted the Fourteenth Annual Meeting of the Mountain-Plains Management Conference. The theme of the meeting was "Management Education: Past, Present, and Future." Among those planning the conference there seemed to be a consensus about the past and present state of management education, but obtaining a prediction of future trends presented a more difficult problem.

The planners theorized that future trends in management education might best be predicted by leaders in education. Not only would these persons be aware of dominant trends, but they would be in academic or administrative positions where their opinions also create the trends. Since it was impossible to gather even a small portion of these people together in one place, the planners decided to use Delphi, in advance of the conference, to collect their opinions and develop a forecast of the future.

Several of the conference planners were familiar with the Delphi technique. One had talked with Norman Dalkey at a professional meeting; one had used the technique in a different context; and a third was familiar with the concept from his teaching in management science, but had not used the technique. The three planners compiled a set of leading questions about future trends in management education. These questions, and a cover letter explaining the purpose and technique, were sent to the panel.

The 60 candidates for the panel represented a variety of schools and professional points of view across the country. Since the number of potential respondents was large, one planner acquired a computer program for processing the responses and for performing the statistical analysis in later iterations.

Approximately 40 percent of the panelists answered the initial request. They responded to 70 statements about trends in management education that might develop in the next 15 years by placing them in one of seven categories from "highly unlikely" to "highly likely." The first were aggregated, refined, and categorized for future iterations. The results were then provided on a computer-generated form. Model responses and interquartile ranges were indicated, as well as the absolute number of responses recorded in each category.

After the initial questionnaire, the procedure was iterated twice. Those respondents who deviated from the majority were asked for comments to support their positions after the second iteration. General comments from all panelists were also requested. After the third iteration the researchers constructed a consensus statement and minority statements when appropriate. Lack of time prohibited further iterations. The results of the forecast were mailed to the participants.

At the conference the participants were also asked to rate the statements generated by the second iteration. Their responses were processed by computer, and they compared their distribution of opinions with that of the expert panel in a review session on the second day of the conference. This process provided a good opportunity not only to demonstrate but to utilize the technique, thereby facilitating its future use.

This use of the Delphi technique was judged to have been a success by the conference program planners, the conferees, and the panel of respondents. The conference planners had been able to obtain, at a total cost of under $200, the opinions of many of the most prestigious management educators whose judgments would otherwise have been difficult and expensive to obtain. Those respondents of lesser professional stature had in no way been intimidated by those of greater prestige. The second and third iterations had shown considerable convergence in the range of responses.

Finally, comments submitted by those deviating from the majority showed they had thoughtfully contemplated the experts' responses to the 70 statements. In general, both the panel of experts and the conference participants were highly complimentary of the procedure and the data it yielded. Only time will reveal the degree of accuracy of the forecast.

Additionally, the program planners presented their results to the Academy of Management at its national meetings in 1973, thus allowing others to see their methodology and their evaluation of the procedure. Since that time another potential user has requested a fuller explanation of the methodology and the computer program used to process the data.

**The Validity of the Method**

Although most observers agree on the significant accomplishments of the Delphi technique, a 1974 Rand critique by Harold Sackman attacks Delphi as "basically an unreliable and scientifically unvalidated technique in principle and probably in practice." No at-
tempt is made here to reconcile the opinions of Sackman and the founders of Delphi, but we do present their disparate views and some comments on the reasons for the disparity.

Most managers and forecasters who have commented on Delphi seem satisfied that it is a useful technique. Delphi is normally used only when a lack of data precludes conventional forecasting, and it provides results believed to be more trustworthy than those obtained from alternative methods. Even though little is provable as to why Delphi works (as Helmer and Dalkey stress), many of its users are unconcerned with its theoretical deficiencies. Sackman, in contrast, applies formal tests of the social-scientific method to Delphi and finds it wanting in statistical reliability and adherence to accepted methodological standards. He thus condemns its use. In Sackman's view,

The history of Delphi reveals a highly exploratory and tentative technique that was never validated. Delphi was obviously full of problematic issues and potentially serious flaws, and was treated with some measure of caution and skepticism by its Rand originators before the Gordon-Helmer study (1964) catapulted the technique into international prominence. After that point, the shaky hypotheses on which Delphi rested were apparently transformed into axioms, and Delphi was promoted as an established, proven technique.

Delphi has led a protected existence for the decade it has been actively pursued. From exploratory and tentative beginnings at Rand, it has spread from government to industry and academia, and diversified from scientific and technological forecasting to policy studies and planning, to quality of life assessment. . . . Droves of eminent people and experts from all callings have lent their name, time, and effort to hundreds of Delphi investigations. All this, and undoubtedly more to come.65

J. P. Martino66 has tested the accuracy of Delphi by comparing events with earlier forecasts of Delphi panels. Sackman scoffs at such tests as "bootstrap validation—Delphi validating itself," and cites one of Helmer's published Delphi studies that wrongly predicted the winner of the 1952 presidential election as evidence that "Delphi results will often be untrustworthy." 67 In a 1975 interview, Sackman referred to other cases in the Department of Defense in which Delphi produced short-term forecasts that proved to be inaccurate; however, he could not cite these classified studies.

How valid is Delphi? Dalkey and Helmer recognize the need to strengthen the theoretical bases of the technique. Dalkey began about 1965 to conduct experiments with UCLA students to test the effectiveness of the technique and the factors promoting convergence. He wrote in 1967:

There are many things we do not understand as yet about the information processing going on during a Delphi exercise. Thus, we cannot as yet determine how much of the convergence is due to three different factors which are clearly at work: (1) social pressure, (2) "rethinking" the problem, (3) transfer of information during feedback. Several exercises have been conducted that throw some light on this.68

Dalkey's experiments continue. In a 1974 interview he stated that he believes some interaction is valuable and he is trying to refashion Delphi to obtain such interaction without biasing the judgment of others. He is also experimenting with the ability of groups to judge the relevance and the "solidity" of information (that is, how well it has been confirmed). While persons seem able to judge the relevance of a fact well, they are less able to judge the solidity of a relevant statement. Dalkey has found that the accuracy of a group in judging solidity of information depends on the group's determination of its relevance. If facts are presented in the order of the group's rating of relevance, group accuracy is highest with the first fact and decreases with each subsequent fact. Dalkey is also attempting to create a theory of probabilistic prediction by groups based on a scoring system for individual probabilistic predictions.

Helmer has also called for further experimentation:

Delphi still lacks a completely sound theoretical basis. This is due, largely, to the fact that Delphi, by definition, is concerned with the utilization of experts' opinions and that experts are rarely available as experimental laboratory subjects. Delphi experience, therefore, derives almost wholly either from studies carried out without proper experimental controls or from controlled experiments in which students are used as surrogate experts. It is still an open question which of the many results obtained through this latter kind of experimentation carry over to the case of real experts, and I hope that further investigations in this area will be undertaken.

Further solidification of the Delphi technique, based on careful experimentation, clearly would be desirable, especially in view of the far-reaching applications to which the method in principle lends itself.69

Sackman criticizes the experiments conducted thus far:

Only relatively recently have Dalkey and some of his coworkers made attempts to demonstrate the validity of Delphi primarily with almanac-type items and non-expert panelists such as college students. These efforts, and spotty returns from a small number of other studies mentioned in this review, provide no scientific validation of Delphi. This history of early experimentation and tardy efforts to assess validity reflects a pattern of isolationism from the mainstream of behavioral research.69

A recent study by Van de Ven and Delbecq, published after Sackman's critique, used rigorous statistical techniques to measure the relative effectiveness of
Delphi in comparison with two other processes for making decisions: nominal group technique (NGT), developed by the authors, and interacting group processes. Among other findings, the authors concluded:

... the degree of differences in effectiveness ... between Delphi and interacting groups is important and large. These differences are so convincingly large that the practitioner should change his conventional pattern of using the interacting group meeting process in favor of either NGT or Delphi techniques on applied problems. . . .

In place of Delphi, however, Sackman proposes the use of rigorous techniques of administering questionnaires by trained social scientists. In an August 1975 interview, Sackman revealed that he was in the early stages of a "feasibility study" on a successor to Delphi, a rigorous technique that would avoid the pitfalls that he finds in the Delphi method. If financial support materializes, he expects to publish an outline of his technique, "participatory polling."

Sackman stated in the interview that he believes many knowledgeable observers agree with his views on Delphi. Response to his Rand report has been "generally favorable although a number of Delphi proponents have taken exception. There is a strong vested interest in supporting Delphi." He believes that the great majority of the Rand staff is sympathetic to his view and noted that some members of the staff had recently asked to undertake a Delphi study but were discouraged from doing so by staff reaction.

Professional relationships between proponents and critics of Delphi, while correct by academic standards, have generated strong feelings. Norman Dalkey, when asked about his conversations with Harold Sackman, replied that Sackman has never contacted him directly to explore differences in views on Delphi—a omission that Dalkey considers significant. Sackman pointed to a formal debate—an "adversary hearing" held at Rand in early 1974—between Dalkey and him in which each presented his views before 40 to 50 of the Rand staff. Sackman acknowledges using several of Dalkey's comments in that debate in his Rand report.

The second number of volume 7 of Technological Forecasting and Social Change (1975) is devoted entirely to Delphi and is largely concerned with its validity. Four articles propose new procedures or extensions of Delphi. One article by Hill and Fowles echoes criticisms by Sackman: that Delphi lacks recognized standards for implementation and thus may be administered unreliably; that the evidence presented to support the validity of Delphi results is unconvincing, particularly when the date of the predicted event still lies in the future; and that the evidence of Delphi's methodological validity under test conditions cannot be generalized to all of its uses. Finally, Hill and Fowles criticize the utility of Delphi on the rather weak ground that Delphi is more often used for planning than for policymaking.

Defenders of Delphi, however, stress its utility. Joseph Coates comments: "Delphi is not a way of drawing forth expert knowledge on expert's issues, but rather is an aid to dealing with those most crucial of contemporary societal problems: judgment and wisdom about the future." Sam Scheele remarks that Sackman's criticism misses the point and compares it to a hypothetical inspection of Alexander Graham Bell's laboratory by the Occupational Safety and Health Administration. Scheele concludes: "The Delphi technique can make the process of formulating policy and making of assumptions accessible," by bringing a kind of participation in processes of society to those affected. In what one Delphi proponent refers to as the definitive rebuttal to Sackman, Peter Goldschmidt attacks nearly all of the bases of Sackman's criticism, accuses him of missing the mark, and terms his criticism a political rather than a scientific document. Acknowledging that Delphi applications often have been poorly chosen or poorly conducted, Goldschmidt summarizes:

Some decisions require information that cannot be derived from knowledge, because none exists, nor from empirical study, because this is infeasible or impractical. In these situations, either the decision-maker must rely on his own experience or on the opinions of others who are considered to be more knowledgeable about the subject than he. The problem for the decision-maker is how to secure such expert opinion, and more importantly, how to reconcile differences in the opinions he is offered. Delphi is a way of overcoming this problem.

Analysis of Significance

Past: Rand's retrospective book reviews the accomplishments of Delphi:

Much of the work of the past quarter-century was successful—some of it singularly so—because it clarified major policy issues, changed the attitudes and perspectives of public leaders, and influenced events in important ways. Or because it resulted in new ways of thinking about the problems of government and new methods for dealing analytically with them. Or because it brought about a synthesis of existing knowledge for application to new problems. Or simply because it added to the common fund of what is known about the world and how it operates.
Present: As the section on "Applications" shows, Delphi is widely used in government and industry. Its simplicity and economy make it attractive to small industries engaged in technological forecasting.

Future: Lawrence H. Day of Bell Canada forecasts a bright future for Delphi in the corporate environment. In so doing, he describes several modifications of Delphi techniques:

The near future should see continued rapid expansion of the Delphi technique in business. The methodology appears to be currently reaching the "faddish" stage. Many low quality studies (which may be mislabeled "Delphi") will be conducted. This could result in a credibility gap with those trying to use the technique to its best advantage. If this credibility gap does occur, there may be a numerical decline in the number of studies conducted, but a general improvement in the overall quality of corporate Delphi research.

Widespread use of the methodology will result in continued rapid modification of the original RAND design. Mini-Delphi's will be used to develop specific forecasts or evaluate potential policy changes. The latter area will receive further attention with the continued development of interest in technology assessment. The use of on-line Delphi techniques will spread, especially as corporate management information systems and remote access terminals become widespread. The availability of standard packages that permit any researcher with access to an on-line Delphi system to act as a study director will also encourage further use of the technique.

Delphi will become popular for certain types of market research studies. This will probably occur more as a result of the promotional activities of market research firms than from the conscious decision of corporate researchers or marketing academics.

In conclusion, Delphi has a healthy future in the corporate environment. This is a future for a whole "family" of Delphi inspired techniques in a broad range of applications. Use of the term "Delphi" to describe a monolithic technique has rapidly become obsolete in this environment. This expanding family of techniques will be the property of the market researcher, market planner, policy planner, systems researcher, etc., as well as the long term business planner.

Appendix 1

Experiment I

Group 1, Group 2: Round 1, Day 1

The experiment in which you are taking part this afternoon is one of a series investigating human information processing. Your primary task will be to answer twenty questions of a general information type. You will be given ten questions at a time. In addition, you will take a standardized concept mastery test. The primary questionnaire is not a quiz or an examination, nor is it a test of social influence. We are interested in the way groups use incomplete information to arrive at factual conclusions.

It is not expected that you will know the exact answer to any of the questions. However for most of them you will have some general knowledge that will enable you to make an estimate—an informed guess—of the answer. Your are to make as good an estimate as you can; but in any case, answer every question as best you can. You are not required to give the answers in whole numbers—numbers with decimal fractions are acceptable. The time allowed is 17 minutes for each set of 10 questions, so you will have about a minute and a half per question.

In addition, you are asked to rate the questions with respect to the amount of knowledge you feel you have concerning the answer. Do this as follows: before giving any answers, look over the questions and find the one that you feel you know the most about. Give this question a rating of 5 in the box on the left labelled "self-rating." Then find the one you feel you know the least about, and give this a rating of 1. Rate all the other questions relative to these two, using a scale of 1, 2, 3, 4, or 5. Thus, a question about which you know almost as much as the one you rated 5 could also get a 5 rating. One that you feel is roughly halfway between the one on which you are least informed and the one on which you are best informed would be rated 3, and so on. Notice that the rating is purely relative, and depends only on how much you feel you know about the question. Do not try to make refined estimates of these ratings, but be impressionistic.

Do not discuss the questions or the experiment with any of the other participants. Feel free to leave the room if necessary, and feel free to smoke. The experimenter will be available during the session if any questions concerning your task should arise. Notice that there is an additional form on which you should record your answers before the questionnaires are collected.

Group 1: Round 2, Day 2

Your task this afternoon will be to reconsider your answers to the twenty questions you worked with yesterday, and make any revisions which, on second thought, you feel are called for. The questionnaire has a record of your answers of yesterday in the left-hand column. Do not hurry, but rethink each question, considering whether there were factors you might have overlooked, or computations which might have contained numerical mistakes. However, keep in mind that you are still being asked only for your best estimate, based on what you know.

There is an additional form on which you should record your present answers before the questionnaires are collected. You will save this record of your answers for the second part of today's session.

Group 2: Round 2, Day 2

On this round, you are to reconsider your answers, this time taking into account some information concerning the responses of the other participants on the preceding round. You have your record of your previous answers. In addition, the questionnaire has a description of how the answers of all the other participants in your group were distributed. This description is given in terms of the Median and the Quartile interval, \( Q_1 - Q_3 \). The median is the middle response for that question. The quartile interval, \( Q_1 - Q_3 \), contains the middle 50 percent of the responses; its size gives you some indication of how widely the responses differed from one another.
Taking this new information into account, you may revise your answers where you think it appropriate.

**Group 1, Group 2: Round 3, Day 2**

On this round you are being asked to reconsider your estimates in light of the changes in estimates by the group on the last round. Your questionnaire has the summary of the group's second responses, and you have your record of your own answers. Please record your present answers below the first set on the answer sheet.


### Appendix 2

The following extract is quoted from the list of questions used in Delphi experiments ordered on group accuracy in Round 1.

<table>
<thead>
<tr>
<th>Question</th>
<th>Error</th>
<th>True</th>
</tr>
</thead>
<tbody>
<tr>
<td>213. What was the number of volumes in the UCLA library system as of June 30, 1967 (in millions)?</td>
<td>.600</td>
<td>2.47</td>
</tr>
<tr>
<td>215. How many B-52's did the U.S. Air Force have in operation as of June 30, 1967?</td>
<td>.616</td>
<td>540</td>
</tr>
<tr>
<td>216. How many calories are there in a pint of 80-proof gin?</td>
<td>.629</td>
<td>1066</td>
</tr>
<tr>
<td>217. How many mobile homes and travel trailers were manufactured in the United States in 1965?</td>
<td>.754</td>
<td>324,000</td>
</tr>
<tr>
<td>218. What was the popular vote in millions for Taft in 1908 when he was elected President of the U.S.?</td>
<td>.759</td>
<td>7.68</td>
</tr>
<tr>
<td>219. How many nonwhite children (in millions) under 5 years of age were there in the U.S. in 1965?</td>
<td>.761</td>
<td>3.27</td>
</tr>
<tr>
<td>220. What was the total number (in millions) of telephones in use in the U.S. as of December 31, 1940?</td>
<td>.770</td>
<td>22</td>
</tr>
</tbody>
</table>


### Notes

2. The use of controlled feedback of group responses in Delphi is based on a social psychological theory that the individual respondent is more likely to alter his judgment and move toward the consensus of the group if he holds his opinion weakly. If he has substantial confidence in his judgment, however, he is less likely to alter it. See, for example, Solomon Asch, "Studies of Independence and Conformity, I: A Minority of One Against the Unanimous Majority," *Psychological Monographs*, volume 70, number 9, whole number 416, (1956).
4. "A quite convincing group of studies has shown that the group opinion is likely to be highly influenced, if not determined, by the views of the member of the group who does the most talking, and that there is no significant correlation between success in influencing the group and competence in the problem being discussed" (Norman C. Dalkey, "Delphi," paper presented to the Second Symposium on Long-Range Forecasting and Planning, Alamogordo, New Mexico, 11-12 October 1967, Rand Publication P-3704, page 5).
10. Ibid.
12. This section draws on several sources: two Denver Research Institute reports, Aerospace Management Techniques (1971), and Contract Research and Development Adjuncts of Federal Agencies (1969); Rand 25th Anniversary Volume (c. 1973); and personal interview with Norman C. Dalkey, 12 August 1974.
13. In the late 1960s the RAND Corporation dropped to lower case the last three letters of its name. For clarity, "Rand" will refer to the corporation and "RAND" will refer to the continuing Air Force Project from which the corporation still draws much of its funding.
14. The RAND Corporation: The First Fifteen Years (Santa Monica, California: The RAND Corporation, November 1963), page 2. See also Bruce L. R. Smith, The RAND Corporation (Cambridge, Massachusetts: Harvard University Press, 1966), page 30. In ensuing years, although Rand's sponsorship has become more diverse, the U.S. Air Force continued to fund Project RAND as a line item in the Air Force budget. Project RAND now represents about one-third of Rand's total research effort.
15. Dalkey interview.
18. Dalkey interview.
30. Ibid.
33. Dalkey interview.
34. The Futures Group developed "interview Delphi," in which a questionnaire is replaced by a carefully prepared face-to-face interview. According to Wayne Boucher (who designed and led the first study), panelists may be uncomfortable with the inflexibility and space limitations of questionnaires; they can say what they wish in an interview. More important, it is possible to insure that the questions being asked are understood and that they are the appropriate questions.
35. Rand Bibliography.
43. R. E. Park, The Growth of Cable TV and Its Probable Im-
pact on Over-the-Air Broadcasting (Santa Monica, California: The Rand Corporation, December 1970), P-4526.
44. Norman C. Dalkey, Quality of Life (Santa Monica, California: The Rand Corporation, March 1968), P-3805, pages 14-15.
45. Norman C. Dalkey, Ralph Lewis, and David Snyder, Measurement and Analysis of the Quality of Life: With Exploratory Illustrations of Applications to Career and Transportation Choices (Santa Monica, California: The Rand Corporation, August 1970), Memorandum RM-6228-DOT, page v.
51. Deane N. Morris, Future Energy Demand and Its Effect on the Environment (Santa Monica, California: The Rand Corporation, September 1972), R-1098-NSF.
53. This program had been developed by Vaughn Huckselt at the Western Interstate Commission for Higher Education, located in Boulder, Colorado.
59. Helmer, "Foreword" to The Delphi Method, page xix.
60. Sackman, Delphi Assessment, page 65.
After the Second World War, the successful military use of mathematical simulation prompted efforts to "model" social and economic systems as well. The following account describes one such effort. The Rand Corporation, which developed many techniques of simulation, studied the dynamics of the flow of financial securities in 1969. Rand was charged with finding ways to relieve backlogs of unfulfilled orders and to reduce the increasing frequency of failures to complete transactions. We shall see that their mathematical model and the conclusions from it had disappointingly little utility to the industry, though in sum we need not label them a total failure.

Carole Cristiano has described several factors that interviewees believed were at fault. Executives of the American Stock Exchange and Rand informally agreed on the study in advance of a contract. A problem arose when the larger, more conservative New York Stock Exchange, which played no part in early discussions, accepted cosponsorship and looked differently upon the difficulties of the securities exchange industry. The New York Exchange advocated a stock certificate depository and instructed Rand to study it. The Amex, however, had wished to give Rand free rein to build a model of stock flow and then to optimize that flow by varying standing conditions of the system. The conflict apparently was never resolved.

A third sponsor, the National Association of Securities Dealers, played a minor role in setting the direction of the study.

Both the contractor and the sponsors committed mistakes. Fragmented supervision and contrary goals of the cosponsors led to some confusion among Rand researchers. Rand seemed unwilling to accept the role of advocate of reforms, which in fact it could not avoid, but chose to couch its results in the language of "cost-effectiveness." Rand was also unwilling and probably would have been unable to include social and external economic factors in its model. Thus, while the model highly rated a full stock certificate depository because of an excellent cost-effectiveness ratio, it could not estimate bankers' and brokers' resistance to the depository, which would emerge from the prospect of changes in regulations and losses in profit to the banks.

In addition to these errors, there existed a weakness in the Monte Carlo technique, which was employed in the simulation. Random variables and statistical samples produced on a computer could not be reproduced without such a machine. Thus, step-by-step analysis of the rationale of Rand's complex program was nearly impossible, especially because the results of that program covered thousands of sheets of green and white paper. Rand's study lost credibility among securities exchange officials. Like an eccentric theory published in a professional journal, the model met no resistance nor spirited discussion. According to the account, the sponsors neither comprehended nor accepted it.

Probably all of these problems reduce to one fundamental error: The Rand researchers, largely unaided by their sponsors, failed to consider the entire system of securities flow. Those components that they excluded—the social, political, and unquantifiable economic—exerted such a perturbing influence on the real system that their absence in the model invalidated it. Indeed, it is an unfortunate but widely acknowledged fact that such components usually cannot be included in a quantitative model, and one is therefore obliged to conclude that some social systems may not be simulated on a computer. To discover limits of validity of mathematical simulation, however, is in itself valuable. Cristiano's illumination of some of these limits is the major result of her study.

During the late 1960s and through early 1969, the financial securities industry enjoyed general prosperity because of rising prices and high volumes in trade. At the same time, however, the industry was burdened by great quantities of paperwork and by an increasing number of failures to complete security transactions on settlement days. Members of the securities community had discussed many suggestions for improving this situation, but no one had been able to adequately define the problem and evaluate proposed solutions.

In early 1969 representatives of the American Stock Exchange (Amex), the National Association of Securities Dealers (NASD), and the New York Stock Exchange (NYSE) met with representatives of the Rand Corporation, a research organization with strong ties to the U.S. Air Force noted in the previous study. After considerable discussion, Rand proposed to develop a mathematical model to simulate the process of trade completion and to provide a method for evaluating proposals that might reduce the level of incomplete transactions.

In this paper we discuss the adaptation of mathematical simulation to some problems of the securities industry. The experiences described in the study illustrate some of the difficulties in transferring technical methods between economic sectors, which arise when
their leaders have different goals and differing views of the role of technology.

**Description of the Technique**

Simulations generally employ simplifications of reality—physical or mathematical “models”—that more or less accurately portray the features of a real system. They are particularly useful for solving problems of “systems analysis” when the complex systems under consideration cannot be analyzed using formal analytical methods.\(^1\) Frequently, simulations represent mathematically the interactions of components of systems. Such mathematical models lend themselves to computer manipulation, for computers provide the means for rapid and thorough search of optimum solutions.\(^2\)

Of all computerized mathematical simulations, the Monte Carlo method, a technique that was developed during World War II, is one of the most frequently used. Monte Carlo methods use random variables evaluated by an artificial sampling experiment to simulate the results of a real process. Although they have been in use for more than three decades, during the last 10 years these methods have found extensive use in the fields of operations research and nuclear physics.\(^3\) Problems handled by Monte Carlo methods are of two kinds: probabilistic and deterministic. The former are concerned with the behavior and outcome of random processes, while the latter show probabilities of a range of theoretically determinate events.\(^4\) A Monte Carlo program can even be used to develop an approximate answer to such a deterministic problem as evaluating a definite integral.\(^5\) In a probabilistic problem, the simplest Monte Carlo method supplies a model with random numbers, chosen in such a way that they simulate the random process of the original problem. The researcher then infers the desired solution or modification of his model from the response of the model to these numbers.

Monte Carlo was first used on a large-scale basis in the Manhattan Project. Researchers there simulated the probabilistic problems of diffusion of neutrons in fissionable material. In early development of the Monte Carlo technique, John von Neumann and Stanislaw Ulam introduced methods to reduce the variance of statistical samples. That is, they reduced the uncertainty in the degree to which the behavior of a random sample differs from the behavior of the whole. Variance-reducing vastly improved Monte Carlo by lessening the need for large numbers of observations while maintaining the reliability and accuracy of the method.

Enrico Fermi, von Neumann, and Ulam popularized the use of Monte Carlo technique among physicists in postwar years. While it is applicable only to some special problems, years of research and high-speed computers have made it a practical tool in many kinds of analytic simulation.\(^6\)

**Simulation at Rand**

Two years after incorporation, Rand began in 1950 to diversify its sponsorship. In addition to Air Force R&D activities, Rand undertook work for the Atomic Energy Commission. In 1959 the Advanced Research Projects Agency of the Department of Defense and the National Aeronautics and Space Administration became research sponsors. In the early 1960s the National Science Foundation, the National Institutes of Health, and the Agency for International Development in the Department of State were added to Rand's list of government clients.

Limited research on civil issues had begun in the mid-1950s, but it was rapidly expanded in the 1967–1968 period, and by 1969 Rand's funding in civil research constituted almost one-third of its annual budget.\(^7\) In its diversified work, staff members often used techniques developed or refined in Rand's aerospace research. Simulation, operations research, and systems analysis were employed to deal with problems of national defense and management of air craft maintenance. The Monte Carlo method was one of several kinds of simulation employed to solve complex problems of Air Force management.

In the 1960s the Air Force performed simulation studies under Project RAND that utilized Monte Carlo techniques employed later in Rand's analysis of the financial securities industry. Among these were numerous studies of proposed systems for maintaining Air Force bases.\(^8\) Two persons involved in the stock exchange study (John Lu and James Peterson) were also participants in these Air Force studies. Robert Petruschell, principal investigator for the securities industry simulation, and several of his colleagues had been peripherally involved in them and had participated in other studies using Monte Carlo methods.\(^9\)

**Needs of the Financial Securities Industry**

In 1969 it became apparent that the securities community had several complex problems, which
needed independent evaluation. Since the beginning of the 1960s, both major exchanges (NYSE and Amex) had experienced difficulty in handling the ever-increasing volume of securities transactions. A large (and unforeseen) increase in volume created even more serious problems for the industry in early 1969. The orders caused backlogs of paperwork in broker-dealer operations and an increasing number of incomplete transactions. Unprecedented numbers of customer complaints drew critical attention from the exchanges, the National Association of Securities Dealers, the Securities and Exchange Commission, and from the Congress.

The Senate Committee on Banking, Housing, and Urban Affairs considered scheduling hearings to find solutions to these problems, which many thought would become more severe. Members of the industry wished to develop their own solutions to these problems prior to the hearings.9 Several approaches were taken to obtain these solutions: NYSE retained John Cunningham as executive vice president of the exchange to implement a NYSE plan for a central certificate depository; North American Rockwell was contracted to perform a systems analysis of the paper flow and to recommend ways to expedite this flow; Ernst and Ernst was retained to state the problems of and find the solutions to maintaining accurate day-to-day accounting records; and Amex approached Rand to study and to recommend long-term improvements within the exchange process.10

Origins of the Rand Study

Rand became involved largely because of a friendship between Ralph Saul, president of the American Stock Exchange and former director of Trading and Marketing for the Securities and Exchange Commission, and David Novick of Rand. Informally Novick and Saul had discussed some problems of the securities industry, especially the greater frequency of incomplete transactions. They agreed that if the industry were to solve its problems it would need a thorough analysis by an independent organization with experience in solving complex problems—an organization like Rand. Saul and Novick began to discuss the possibility of letting a contract to Rand. At that time, Amex could not describe the problems of the industry in a form usable to Rand, but Rand was hired to perform a two-month exploratory study to observe the problems and to define what, if anything, its researchers could do to assist the industry in solving them. Because Rand has been restricted by its charter to undertaking research in the public interest, it was prohibited from working for Amex alone. Therefore, a contract to Rand was sponsored jointly by Amex, the New York Stock Exchange, and the National Association of Securities Dealers. While its "public" nature was thereby assured, the project became much more difficult because of its multiplicity of sponsor interests.11

Rand concluded the initial study by proposing to analyze the entire structure and the transaction process of the financial securities industry. By developing a Monte Carlo simulation model they would study the trade completion problem. The model would generate data for daily trading activity of the exchanges, uncompleted trades, and stock loan practices. It would simulate major characteristics of the trade completion process, such as stock delivery priorities, stock borrowing and segregating policies, stock clearing processing rules, and others. All processes involved in the flow of stock certificates essential to settling trades on any exchange or in the over-the-counter (OTC) market were to be modeled.

The advantages of using such a technique were summarized by Rand:

1. The real system continued to function without disruption during the experiment.
2. By eliminating processes of the real system that are extraneous to the problem being studied, the effect of proposed changes on the process under study can be more clearly observed.
3. A large number and range of changes can be examined quickly and at low cost.
4. Proposed changes can be studied singly or in a variety of combinations to determine their effect on the system and on each other.12

Although there were differing perceptions of the scope of Rand's research, the proposal was accepted, and a $1.2 million contract among the three parties was negotiated. While Rand and Amex interviewees recalled in 1974 the immediacy of the problems and the need for solutions that could be easily implemented, an Amex press release gives some credence to the NYSE perception of a more long-term nature of the work.

Rand staff members found it necessary first to study the securities exchange process that they had proposed to model. This task was difficult for a number of reasons. First among them were problems in establishing a working relationship with staff members of NYSE and NASD. While the top management of Amex was enthusiastic about the study, NYSE management was
willing to do little more than fund the study. Former
staff members of NYSE state that management had al­
ready determined its solution to the problems of the
exchanges—the establishment of a certificate deposi­
tory. The Rand study was considered superfluous; it
was an "insurance policy," a hedge against coming
political problems with the Securities and Exchange
Commission (SEC) and members of Congress. NASD
was also involved in the study but saw its role
primarily as an aid to OTC dealers, touting NASDAQ
(a computerized automated trading system for OTC
securities), and otherwise staying out of the way.

Conducting the Study

Because of the lack of enthusiasm on the part of the
top executives of NYSE and NASD, their staffs did not
participate fully in the development of the project.
Robert Petruschell, principal investigator of the Rand
team, estimated that the team spent considerably
more time with the Amex staff alone than they did
with the two other staffs combined. He feels this was
due primarily to the fact that the study had been en­
thusiastically endorsed by Ralph Saul, who urged his
staff to cooperate fully with Rand. Former staff
members of NYSE agree that the study was initially an
"Amex baby," and they attribute their continuing lack
of enthusiasm to their impression that the study be­
came even more of an Amex concern as it progressed.
John Alexander, then employed at NYSE, states that
the Rand study team held only a few meetings with
him. The Rand researchers preferred to work most of
the time in California, making infrequent visits to New
York to consult primarily with Amex staff members.
When Alexander did meet with them, Rand research­
ers did not seem receptive to his suggestions and his
offers of NYSE automated sources of data. Similar
experiences were reported by other NYSE staff mem­
bers and, as a result, their enthusiasm for the study
waned. It is apparent that in the close-knit, informally
communicating securities community both Rand re­
searchers and middle-level managers sensed the top
administrators' enthusiasm or lack thereof and reacted
accordingly.

Rand researchers spent a substantial amount of
time and project money familiarizing themselves with
securities exchanges. The Rand report of December
1970 described the major features of their model of
this process. Some, such as the transfer agent, were
represented at a high level of aggregation; others,
such as back-office activities, were represented in more
detail. The model simulated the flow of stocks origin­
ating from trading in a single issue through the back
office of a sample of firms representing the industry.
More specifically, the model was developed to perform
the following functions:

1. Simulate daily trading activities.
   a. Generate the shares traded per day for a given issue.
   b. Allocate these shares to firms and customer types in the
      model according to their respective portions of the
      market.
   c. Simulate errors due to "uncompares." 14
2. Simulate resulting back-office operations.
   a. Determine security due-ins and due-outs.
   b. Determine segregation requirements.
   c. Borrow and lend stock.
   d. Receive and deliver certificates.
   e. Keep an aggregate version of a firm's stock records.
3. Simulate the clearinghouse operations.
   a. Net each firm's trade.
   b. Allocate net positions.
4. Simulate delay times of transfer operations.
5. Record the levels of various kinds of failures to complete
deliveries.
6. Estimate the financial implication of failures for each firm.
7. Calculate operating statistics for selected brokerage firms and
   throughout the industry. 18

After the basic model was created, the researchers
established a benchmark case to represent the existing
system of trading on the NYSE at a volume of about 20
million shares per day and at an average price of $35
per share. The model was used to generate "fails to de­
deliver" in the benchmark case and the cost incurred by
brokers due to these fails was calculated. Then several
alternatives to the existing system of trades were tested
by introducing one or more changes. The costs of the
resulting fails were added to the costs of introducing
the changes, and the sums were compared to the cost
in the benchmark case. In the analysis of alternative
clearing systems for over-the-counter stocks, a similar
procedure was followed: the cost to the members of
the securities community of the existing system of
clearing was compared to the costs of two alternative
clearing systems. 19

The Rand team had conceived the model to be a re­
usable tool for the securities industry. They felt the
model was sufficiently well designed to be of assistance
in solving new problems as well as those they had ad­
dressed. Amex staff members agreed. NYSE staff,
however, did not feel that the Rand staff adequately
demonstrated that the model was an accurate repre­
sentation of the exchange process. In addition to their
skepticism about the model itself, NYSE staff members were disappointed with the alternatives that Rand chose to analyze. Rand had focused on the probable effects of immediate solutions to current problems. It was only at the insistence of NYSE that Rand considered any long-range solutions, specifically, the establishment of a full depository.20

Rand staff members did not feel that their charge was to make recommendations but merely to indicate probable results of variously changing the securities exchange process. Yet many interpreted several of Rand’s alternatives that were obviously cost effective as recommendations.21

Alternatives shown to be particularly cost effective were as follows:

1. A change in priorities of delivery of stock certificates, the most important aspect of which was giving first delivery to brokers rather than to institutional customers.
2. The installation of high-speed computers to reduce time of transferring stocks.
3. The implementation of a system to require member firms to make stock loans to cover “fails to deliver” by other brokers, thereby lowering the rate of broker-to-broker fails.
4. The initiation of partial delivery rules, installation of an interbank wire system, continuous monitoring of stock inventories, and the implementation of a “Floor Derived Clearance System” to reduce broker-to-broker fails.
5. The initiation of a full-stock certificate depository, incorporating the first four changes.22

Petruschell presented the technical results of Rand’s research and the effects of the suggested changes to the sponsoring organizations and other members of the securities community. He was confronted with no serious argument. He felt that the results were sound and the considerable value of a number of the changes warranted that some be introduced. The researchers also felt that the model would continue to be used.23

Implementation of Results

In interviews conducted in September 1974 and July 1975, several individuals in the securities industry who observed the Rand study and its consequences indicated that some of the changes were implemented.

High-speed computers have been installed in major banks and in the exchanges. The procurement of these computers and their use in a program to reduce transfer times was directed by a Banking and Securities Industry Committee (BASIC), which set time standards for transfers. These transfers could be met only with computers.24

Amex and BASIC rules now require dealers to follow uniform procedures for partial deliveries. This decision was influenced in part by the Rand study.25

A depository for stock certificates, acknowledged by staff members of both exchanges to be the best long-term solution, has been implemented. Tom McInerney, president of the Financial Services Division of the Automatic Data Processing Corporation and former vice president in charge of Operations Planning at the Amex, stated that the depository has revolutionized processing in the securities industry and has far exceeded the expectations of the most optimistic members of BASIC. Participation has increased, and partnerships with regional depositories have been formed. McInerney stated that implementing the depository was “the single biggest operational step the securities industry has taken in 20 years to solve its problems, cutting certificate movements by 75 percent.” Severe problems in the early stages, according to Petruschell, were due in large part to a doubling of paperwork in a two-phase transition period. The firm of Arthur Young and Company was retained by NYSE to analyze the clerical problems in late 1970-1971. In the end they solved many of those problems. McInerney feels that the Rand study helped to advance the depository and gave credibility to its continued development, despite the initial problems. However, he and Petruschell agreed with John Cunningham that the depository was timely and that it would have been implemented without the Rand study.26 As is further explained below, the present depository is not the “full” depository recommended by Rand. Hence its ability to reduce the number of incomplete transactions is less than Rand predicted.

There were several alternatives that were not implemented for a variety of reasons. Among them, there were no changes in the priorities of delivery of stock certificates. Giving first priority to brokers would have eliminated more fails by eliminating chain reactions of nondelivery from broker to broker. The securities system as a whole would have benefited, but rarely would a broker give priority, for the good of the system, to other brokers before satisfying the needs of his customers. Brokers sensed that individually, in the short run, they would not benefit from the revised system, so they did not initiate the change.27
The industry did not adopt a system for mandatory loaning to brokers of stock to cover fails. Many brokers (especially in the larger firms) preferred to control an inventory of stock certificates or to loan to other brokers at their discretion rather than on demand.28

The Floor Derived Clearance (FDC) System has not been implemented. This was due in part to the fact that during the final phases of the study, there was a drop in trading, and the urgency of the crisis disappeared. Paul Kolton, former executive vice president and now chairman of the board of Amex, stated that the need for such a system was further reduced by the establishment in 1972 of the Securities Industry Automation Corporation (SIAC), a subsidiary of both exchanges. It focuses on the problems of initial transactions rather than on those in back offices.29 SIAC differs from Rand’s FDC system in that SIAC depends on brokers to submit lists of all transactions, while FDC would have recorded the transaction when it was made on the floor of the exchange. Harry D. Todd, formerly of Amex, stated that FDC would have been much more efficient. He believes that, as exchange needs become more complex and computer technology becomes more sophisticated, its future implementation is almost inevitable. John Cunningham agreed, while Alexander and Mclnerney felt that the goals of FDC can be reached more efficiently through other systems. All agree that SIAC works well enough to have discouraged any major campaign to change the system immediately.30

Movement of certificates has not been halted. Some banks and brokerage firms were legally required to maintain the certificates in their vaults or within their states. They were continually subject to audits, and banks in particular were uninterested in lobbying to change state legislation. The NYSE had sponsored a study of the Uniform Commercial codes of states and had lobbied to modify these laws, but by the late 1960s not every state had made the required changes. Total immobilization was not immediately possible.31

Additionally, all involved agreed that many smaller stockholders throughout the country would balk at allowing brokers to hold their stock certificates in a depository in New York. The securities industry is conservative, and its members may have resisted the mandatory immobilization of certificates because it constituted a major change in accepted procedures. While decision makers did not reject the idea of a depository completely, they did reject one of its major tenets—the retention of the majority of certificates in one place.32

**Perceptions of and Reactions to the Study**

Adopting the Rand approach would have led to a substantial increase in the number of regulations to ensure that the new procedures would be followed. Such an increase would inject unwanted rigidity into the exchange process and would allow individual brokers less flexibility. For this reason, various members of the securities community were highly resistant to the proposed changes.

For example, brokers agreed that a priority delivery system existed informally, but they rejected being forced to recognize a rigid structure of priorities on the authority of Rand’s analytical model. Furthermore, influential individuals within the industry could better advance their positions with a looser structure. Therefore, many large firms resisted this major change. Some of these firms had already introduced the new practices in their organizations, and they had thereby gained competitive advantage. Required changes would benefit the securities community overall, but they would be detrimental to the hierarchy of firms.33

Banks that transfer stock also profited from inefficiency. These influential banks serve as agents for institutional customers and, in New York, as agents for other banks throughout the country. With the existing delivery system, banks could hold a larger number of securities than with the proposed changes. These securities were usable, interest-free holdings.

As an example, consider a person in Los Angeles who requests his bank to purchase 100 shares of a company. The Los Angeles bank will (a) either require cash from the customer or will verify that he has sufficient funds in his bank account to cover the purchase of the stock, and (b) then wire its New York agent bank to purchase the stock, but will not include instructions for disposition of the purchased stock. The New York bank will instruct its broker to purchase the stock as soon as possible. When the broker delivers the stock to the bank, the instructions from the Los Angeles bank have not yet arrived—the receiving window has no knowledge of the transaction. The broker must then borrow funds from the bank to cover the cost of the stock that he has purchased. The bank in Los Angeles earns interest by loaning funds deposited by the original customer, while the New York bank earns interest on funds it would otherwise have to pay to brokers on the receipt of the stock.

Multiplied by the number of such incomplete transactions, interest earned is substantial for the larger
banks. Therefore, there was disincentive to smooth out the system. Transfer agents (generally banks) were unautomated and slow, but “worked all right” and were not enthusiastic about granting favors to brokers, such as rushing transfers and making change, especially at their own expense.\textsuperscript{34}

There were less tangible results of the study. Kolton stated that the study brought new disciplines to the securities industry, giving it a different perspective on its problems.\textsuperscript{35} Despite the intrinsic limits of a mathematical model that simulates human behavior, McInerney agreed that the industry benefited from exposure to simulation by modeling. McInerney felt that the strongest point of the study was its emphasis on the need for banks to change their practices of securities trading. The study reaffirmed convictions of several executives and acted as a catalyst for change.\textsuperscript{36}

Those at Amex who were involved in the study found it to be valuable. Led by McInerney and Todd, staff members worked continuously with the Rand researchers early in the study and were committed to utilizing the model after it was finished. Later Amex made limited use of the system and found it helpful. Its use, however, was constrained both by the lack of enthusiasm that NYSE management displayed and practical problems in using the model. The program was designed to be run on an IBM 360/50 or larger computer, one of which was available only at the New York Stock Exchange. McInerney stated that an annual expenditure of $100,000 per year would have sufficed for three to five persons to modify and test the model on a continuous basis.\textsuperscript{37} Alexander disagreed. He doubted its validity and felt the annual expenditure would have come closer to $300,000 or $400,000.\textsuperscript{38} It was an expense NYSE did not wish to incur. Kolton noted that Amex has presented several strong arguments to NYSE to solicit their continuing cooperation but never obtained a commitment.\textsuperscript{39}

Although never stated, it became apparent that some results of the study were contrary to NYSE policy. Former Amex Assistant Director Todd noted that the attitude of NYSE management became negative after Rand researchers asserted that the particular certificate depository endorsed by NYSE was not essential. Other changes, taken together, could have solved many industry problems sooner. Even a “full depository” would be cost effective but was not required. Because NYSE was committed to the depository, “there was little enthusiasm for supporting an analysis that would continue to undermine previous decisions.”\textsuperscript{40}

Mark Guarino, formerly an employee of NYSE, also implied that this was a major problem. While he accepted the logic of the model, he dismissed the combined alternatives as “unrealistic.” The model depicted results of certain actions, but it could not produce a detailed procedure to bring about the changes.\textsuperscript{41} Cunningham explained that without difficult coordination of the actions of the banking community, the Federal Trade Commission, and the Securities and Exchange Commission, any changes in exchange policy would be ineffective.\textsuperscript{42}

Rand had not been charged with developing detailed recommendations to implement, nor was anyone in NYSE assigned to study even the feasibility of implementing the proposed changes. Neither Rand nor Amex could adequately respond to charges that the results were unrealistic. They could only reiterate their request that NYSE continue to support the model and to assist in the funding of studies of the feasibility of implementation. By this time, however, delivery problems had lessened, NYSE was unhappy with recommendations contrary to policy, and their response to the request was unfavorable. Amex felt that for one exchange to attempt to use the model would be pointless, and it fell into disuse. The goal of Rand that it be a useful tool in planning operations of the securities community was never met.

Analysis of Significance

The Rand simulation model had little impact on the operation of the securities industry, but its problems illustrate the complexity of transferring technological expertise.

Mathematical simulation is one of the most visible computer techniques refined by the aerospace industry. It has great appeal in the abstract, but few persons outside engineering and science understand its range of applications. To be able to accept and to use simulation in less technical problems, one must first understand it.

In the aerospace industry, simulation was a familiar engineering and managerial technique. Aerospace managers, who frequently had technical backgrounds, understood the principles of modeling and had faith in the results. On the other hand, many of the managers in the securities community of 1970 understood the principles of simulation but not the details. In retrospect, this lack of understanding contributed to the skepticism of NYSE managers and the inability of Amex to defend the model.

In several ways Rand staff approached the securities
assignment as if it were a defense contract: the cited interviews suggest that Rand researchers did not take adequate steps to acquaint the staffs of the exchanges with their approach, nor did they report enough to their sponsors. "We asked them for progress reports," said Alexander, "and they acted surprised." 43 Most importantly, they spent the majority of their time developing the model rather than testing and demonstrating its utility to their sponsors. Tom McInerney admitted that even he did not understand the model fully, and he doubted whether anyone other than Harry Todd had an adequate grasp of its potential utility.44 This lack of understanding was compounded by the use of the expansive Monte Carlo program. Petruschell admitted that when one changed the parameters of the model, it was very difficult to determine exactly how the results, which filled a 6- by 18-foot table with a foot-depth of computer printouts, had been achieved.45

The incredibility of the model was exacerbated by other factors. One problem inherent to simulation was magnified in its use in the securities exchange industry. Perhaps 20 percent of technical problems, such as those involved in the aerospace industry, may be qualitative or "social" and 80 percent may be quantitative and easily modeled. In the securities industry, the social elements embrace a substantially higher percentage of the problem. While the simulation of the technical elements of securities exchange may have been as valid as in a technical problem, their smaller proportion of the entire system brought the whole methodology into question.46

In an aerospace company, the goals of individuals coincide with the group goal, which might be, for example, an aircraft that flies. In the securities community, the goals of individuals are often different from those of the researchers who are seeking to increase efficiency of the entire exchange system. While the model defined goals of the industry as a whole, it threatened individual participants. But the model threatened group goals as well when its results conflicted with a standing policy.47

While simulation provided an objective look at the industry and catalyzed some changes, it was not used as a tool to manage the industry. Those who appreciated its potential were not in a position to utilize it, and top management was not committed to establishing an optimum process of securities exchange. When one attempts to apply objective criteria to solve social and political problems, says McCormack of the Securities Industry Automation Cooperation, "you won't make it with a simple number crunch."48

Notes

1. Much of this material is drawn from the following source: Martin D. Robbins, John A. Kelley, and Linda Elliott, Mission-Oriented R&D and the Advancement of Technology: The Impact of NASA Contributions (Denver: Denver Research Institute, 1972).
   T. C. Smith, SAMSOM—Support Availability Multi-Systems Operations Model, (June 1964);
10. Interview, Tom McInerney, Automatic Data Processing Corporation, New York, New York, 1 July 1975.
15. Alexander interview.
16. A trade is uncompared if the firms involved in the trade do not agree on the terms.
17. A DK occurs when stock is presented for delivery and the expected receiver claims no knowledge of the transaction. The receiver says, "I don't know the trade."
20. Alexander interview.
21. Cunningham interview.
25. Ibid.
26. Cunningham interview.
27. McInerney interview, 1 July 1975.
31. Alexander interview.
32. McInerney interview, 1 July 1975.
33. Alexander interview.
34. Petruschell interview, 12 August 1974.
35. Kolton interview.
37. Ibid.
38. Alexander interview.
39. Kolton interview.
40. Todd interview.
41. Guarino interview.
42. Cunningham interview.
43. Alexander interview.
44. McInerney interview, 1 July 1975.
47. Todd interview.
Systems Analysis in the California Studies of Public Services

Carole R. Cristiano

EDITOR'S COMMENT

Carole Cristiano's review of the "California Studies" documents how the techniques of systems analysis were used in trying to solve four broad social "problems" in California. It suggests that systems analysis often may be unsuitable to define or solve such problems, which encompass a diversity of human and technological interactions infinitely more complex than technical developments alone. As more deficiencies in applying the techniques are disclosed in the case, the reader may find his sympathies approaching those of Ida Hoos, who declared: "... the very characteristics which distinguish social from other species of systems render them resistant to treatment ..." There seems to be a principle that underlay all those little things that went wrong, from shoddy workmanship to political naïveté. Perhaps it was the reluctance of humans to be fit into analytical cubbyholes.

After reading Cristiano's account, we must judge the "California Studies" a failure. While one might argue that the technical results of the studies were positive, they were not implemented and there is no chance that they will be. Cristiano, building on an earlier report of her colleague John Gilmore, has identified several reasons for this lack of consequence. The four contractors might have encompassed political forces within their systems, for these dominated the systems in the end. The monitors of the contracts might have focused their problems better at the outset and held their contractors to rigid standards, for the lack of criteria apparently contributed to loosely reasoned arguments. Those who initiated the contracts might have "institutionalized" the studies by introducing them in the California legislature and thus might have gained legal standing for them.

Perhaps the most important lesson of this case, however, is that the strength of systems analysis derives as much from quantitative, detailed descriptions of components as it does from encompassing the totality and diversity of those components. Ironically, one must narrow the analysis, study the minutiae, before one can generalize. Such a method appears bound to encounter problems when it is applied to a state of society whose detailed workings are not even qualitatively understood.

Introduction

In 1964, the state of California encountered increasingly serious economic and social problems. These problems, apparent throughout the country, were more severe in California, in large part because of rapid population expansion. The state had moved from a position as the fifth most populous state prior to World War II to second place by the start of the Korean conflict, and to first place during the mid-1960s. Among the most serious problems were urban congestion and shortcomings in the transportation system, rising educational needs, environmental pollution, and a higher-than-national average level of unemployment.¹

The last problem threatened to worsen because of impending cutbacks in defense and space contracts. More than one-third of the state's manufacturing workers were employed by the aerospace industry, which was largely dependent upon federal funding. In 1964, a year in which California's unemployment was 6.0 percent, reductions in federal aerospace contracting added a further burden to the state.²

Aerospace employees presented a different kind of unemployment problem than did workers in other industries. Employees of aerospace and defense contractors were highly skilled and educated. They provided a reservoir of talent generally presumed competent to study almost any complex problem and to design systems to cope successfully with it.

This situation created an opportunity to match aerospace talents and urban problems on an experimental basis. After informal exploration among aerospace firms by his aides, Governor Edmund G. Brown announced that he would invite these firms to bid on studies to create urban systems in four critical areas. The four systems were identified as follows: (1) an integrated transportation network within the state; (2) a new system to handle California's criminally and mentally ill; (3) a system of collecting information upon which government and industry could base decisions for years ahead; and (4) a system for managing the wastes discharged into the air, soil, and water.

These studies came to be known as the "California Studies": applications of techniques of aerospace sys-
tems analysis and aerospace personnel to domestic problems. This chapter will introduce the techniques of systems analysis in the aerospace industry and will document their applications to the urban problems of California.

Description of Technique

E. S. Quade of the Rand Corporation has completed an authoritative research on the application of systems analysis to the defense industry. He has defined the process as

an analytic study designed to help a decision maker identify a preferred choice among possible alternatives. It is characterized by a systematic and rational approach, with assumptions made explicit, objectives and criteria clearly defined, and alternative courses of action compared in the light of their possible consequences. An effort is made to use quantitative methods, but computers are not essential. What is essential is a model that enables expert intuition and judgment to be applied efficiently. The method provides its answers by processes that are accessible to critical examination, capable of duplication by others, and more or less readily modified as new information becomes available.

In short, "systems analysis" is the formal examination of alternative designs of a system, a tool in a process of rational decision making. This is not mechanized decision making; rather it is a method of supplying helpful information to the decision maker. The actual decisions reflect experience, judgment, and values. The information may be transmitted as (1) a "best" solution, recommended after examining alternatives and accompanied by supporting detail and justification of that solution, or (2) alternatives presented to the decision maker with no recommendations, but with evaluation of the inputs and outputs—the cost and effectiveness—associated with each alternative.

The "systems approach" is a process that involves identifying a problem or threat, learning and describing its environment, and then defining what must be achieved to counter the threat or solve the problem. Alternative plans must be considered, and the most attractive one is then elaborated into the design of a system. The "most attractive" method or system may be selected by rigid "cost-effectiveness" analysis, by intuition and judgment, or usually by a combination of the two. The choice must consider the environment in which the system will work and include deliberate criteria for choosing among the alternative methods.

While the systems approach usually begins with systems analysis, it can be extended to design, engineering, and implementation. Thus, the systems approach can, in theory, be applied to all aspects of solving problems.

History of the Development

Systems analysis emerged in the early 1940s from solving military problems in which intuitive decisions were often too costly and ineffective. Methods, usually quantitative, were developed to describe an operational problem, to determine what information was needed to solve it, and to analyze this information in order to produce the best response. During World War II, operations analysts in the armed services had to use "existing" resources to solve tactical problems: to employ radar countermeasures, to design effective bombing patterns, to deploy destroyers around a convoy. From this experience, systems analysis grew to select and evaluate "proposed" weapons systems. This required that research (on what was technically feasible) match defense requirements (which sometimes were not technically feasible).

Systems analysis could, for example, assist in determining the need for an Army airlift or for a desired mix of airlift and sealift to deliver a fighting force overseas. The analysis would not include the design of the transport aircraft; it would, however, consider the performance requirements that the craft should meet.

The same problems that had fostered the development of systems analysis still existed in its application. The most important of these were: (1) there was little experience with the new weapons and delivery systems; (2) it was often difficult to experiment with some of the real weapons and systems; (3) the technological complexity of new weapons grew rapidly; (4) managing the development, procurement, and maintenance of new weapons systems became more difficult; and (5) there were severe time pressures to solve problems or to counter immediate threats. The technique of systems analysis, however, dealt more effectively with these problems than had prior planning techniques. The hierarchical structure of the military facilitated use of the method and enhanced its reputation as an effective technique of managing. Acceptance of the systems approach was also aided by the circumstance that it made public intervention in defense decision making difficult, because it created the appearance that the public lacked technical expertise.

A Rand Corporation study, edited by E. S. Quade and W. I. Boucher, provides a discussion of many of the
defense applications of systems analysis.\(^9\)

As military analysts gained experience with the new techniques, they began to include national policy and strategy in their analysis. Defense policy and strategy were well suited to the systems approach, because the policy goals were well defined in the 1940s and 1950s. This higher level systems analysis (or policy analysis) was later applied to determining the role of space systems in national defense and to comparing policies of military superiority vs. military parity with the Soviet Union. The mix of forces needed for national defense has probably been the most intensive systems analysis of policy.\(^10\)

Policy analysis has been used extensively by the Air Force. One of the most influential studies was that commissioned by the Air Force in 1951 to analyze the most effective ways to acquire, construct, and use strategic airbases in foreign countries. The Rand Corporation's study determined that national security would be higher and costs would be lower if the strategic airbases were located only in the United States.\(^11\)

**An Application**

During the early 1960s, California's population increased so fast that 200,000 additional jobs were needed per year. In addition, expected increases in the 20- to 24-year-old age group would add another 59,000 to 65,000 persons per year to the labor force. Finally, industrial automation in California would also certainly lead to increased productivity but not lead to a commensurate increase in demand for labor. Even without cutbacks in aerospace work, the already high unemployment rate in California would increase if some action were not taken by the state.\(^12\)

The increasing population and unemployment, primarily concentrated in the urban areas, worsened already substantial urban problems. Pollution and poor mass transportation, inadequate housing, needs for additional welfare assistance, and land use planning all were becoming more urgent. So also was external pressure on state and local governments to construct housing, to subsidize mass transit, and to establish training programs.

Staff members of the California Department of Finance wished to encourage economic development that would provide revenue to the state, employ as many of its citizens as possible, and be diversified and healthy. They were aware that the current revenue base was adequate but fragile.\(^13\) The economy, they also knew, was too dependent on space and defense contracts. At its peak in 1963, aerospace employment was at 510,200. In 1964, that number had dropped by 26,300. Concurrent with the drop in space work, defense contracts awarded to California firms decreased by 13 percent in 1964. One analyst anticipated in 1966 that defense work would stabilize but predicted that space employment would continue to decline.\(^14\)

The stimulus to the development of the "California Studies" had come in December 1962, when the planned $2 billion Skybolt Program,\(^15\) of which California firms were to be substantial beneficiaries, was cancelled. Governor Edmund G. Brown formed an Advisory Panel on Aerospace and Electronics Industries to suggest how to soften the impact of this and future cutbacks. The panel was composed of some 14 executives of major defense companies and several economists invited to study problems of increasing unemployment and future defense reductions. In the summer and fall of 1964 the Economic Development Agency and the Department of Finance began to investigate with this panel how the state might ease the impact upon the economy.\(^16\)

Even though there was agreement that the aerospace industry and the state government could help each other, the form of mutual assistance to be undertaken was not obvious. Aerospace firms were accustomed to responding to requests to solve specific technical problems. Procurement and techniques of project management similar to those used by the Department of Defense and the National Aeronautics and Space Administration would increase the probability of obtaining a useful product—but very few knew what the "product" should be. As discussions progressed, it became evident that it was a "process" instead of a product that needed to be identified. The problems confronting California were complex and their potential solutions remained undefined. It was thought that aerospace firms could use systems analysis to define the problems and to design programs that might solve them.\(^17\)

A plan developed out of meetings between the panel and the state agencies. The state was to offer requests for proposals (RFP) to the aerospace industry to study the problems of the state. In preliminary discussions aerospace firms were receptive to the idea.

Governor Brown scheduled a one-day symposium on "California's Search for New Sources of Economic Growth," at which he formally announced The California Aerospace Study Program. The announcement was made on 14 November 1964, with much fanfare. A great deal of publicity accompanied the issue of the
RFPs. They were sent on 17 and 18 November 1964, and proposals were due 18 December 1964. The studies were to have a fixed price of $100,000 each, theoretically to allow state administrators to evaluate all proposals on performance alone.18

RFPs were employed to guide the prospective contractors, but state administrators were not sure what they wanted from the bidders. They did not know the dimensions of the problems, nor did they prescribe the kinds of solutions that would be needed. The RFPs were designed to encourage bidders to propose creative approaches and to deal systematically with the problems. The wording of the requests was therefore as general as possible.19 While this allowed maximum flexibility, it gave the contractors few guidelines and reduced the chances that their products would be of use to the state.

Many aerospace firms were unaccustomed to dealing with vague objectives, but several were interested in diversifying. Thirty-one bidders, substantially less than half of which were California aerospace firms, submitted 50 proposals in the four areas. Despite this fact, ultimately, all four of the studies were awarded to large aerospace firms based in California. All of the companies that were awarded contracts had planned continuous efforts to diversify their product lines and had a high percentage of their employees engaged in research and development. Contracts were let by February of 1965, each for $100,000 and each for a duration of nine months.20 The projects were the following:

1. The Lockheed Missiles & Space Company undertook to design a statewide information handling system and to develop a plan to implement it.
2. Space General Corporation (a subsidiary of Aerojet-General Corporation) explored the feasibility of applying techniques of systems engineering and of operations analysis to social problems. They were also to recommend a program for prevention and control of crime.
3. The Aerojet-General Corporation was to assess the suitability of systems analysis and systems engineering to manage waste in California. They were also to outline research and development to be undertaken in the first stage of a broad program.
4. North American Aviation, Inc., was to specify systems to solve problems of transportation.21

The studies were funded without a specific appropriation from the legislature—a legal, but impolitic action on the part of the governor. Money was allocated from appropriated, but unspent funds. In some cases, such as in the transportation study, the original purpose of the appropriation could have been construed broadly to include the study. In others, however, especially those on waste management and information systems, most of the funds were clearly intended for other purposes. Legislative leaders James R. Mills, Jesse Unruh, and others voiced some resentment, which was not focused on the new uses for the funds but on the way in which the legislature had been ignored in negotiating the entire program.22 This would not aid the fortunes of the recommendations in the study.

Despite these grumblings, the four contracts were awarded, and the work was performed within the prescribed time. The "California Statewide Information Study" contained a general description of patterns of flow and storage of information, a proposed statewide information system and the benefits that would result from implementing it. The study also contained a step-by-step plan to implement the new system, the associated costs, and suggestions of how to finance its development and operation.23

"Prevention and Control of Crime and Delinquency" described existing methods for dealing with crime and delinquency and recommended a plan for developing a new system of criminal justice. A "Master Plan" included schedules of eight programs, ranging from more efficient administration of the existing system to innovative programs such as one to create more jobs. The schedule for implementation called for a phase to study the need for each program and contained estimated costs of the Master Plan.24

Aerojet-General's "California Waste Management Study" described the problems of refuse and sewage handling and evaluated methods to dispose of it. The study described the systems approach and its applicability to "waste management," compared costs and listed the functions of several systems, and produced a plan to design one comprehensive system.25

The "California Integrated Transportation Study" was conducted under the joint sponsorship of the state of California and the Bureau of Public Roads of the U.S. Department of Commerce. Researchers developed a model and demonstrated its applicability to several problems. They then planned a program for an integrated transportation system in California.26

A fifth contract had been awarded to System Development Corporation (SDC). This company served as liaison for the firms engaged in research and, perhaps more importantly, sought federal funds to implement the studies. After their submission, SDC was also re-
tained to evaluate the final studies. SDC reviewed the four final reports for soundness of technological and methodological assumptions and for feasibility in applying systems analysis to major public problems and reported the results to the state liaison officer.

One report, North American's "Integrated Transportation," was rated excellent; two reports—Aerojet-General's "Waste Management" and Space General's "Prevention and Control of Crime and Delinquency"—were ranked lower but deemed well within the range of acceptability; and the Lockheed Missile & Space Company's Information System received special positive comment. This study, according to SDC, represented an enormous amount of work—far more than the state could have expected for its $100,000 investment. (It is interesting to note that the most favorably reviewed studies were those that addressed the more technical problems.) In December of 1965, the Department of Finance indicated its satisfaction with the contents of the four studies:

...[They] in and of themselves, have been notably successful. They have introduced new ways of thinking, new concepts to many of the agencies involved. They have generated even in offices not involved in the studies themselves, an excitement about these and other things that government can do. The specific recommendations of the studies have a good chance, by and large, of implementation.

Little was done subsequently, either in follow-up study or in implementing program recommendations. John Gilmore and others reviewed the California aerospace experience in July 1967, analyzing the successes and failures of the studies. The following section is derived mostly from their work, supplemented by more recent information.

Analysis of Significance

It is unclear whether the studies were beneficial to the four contractors who performed them. Each spent far more than $100,000 on the studies. (Estimates of the out-of-pocket costs to each company vary between $50,000 and $200,000.) Ten years later, there have been no profitable follow-on studies. Although aerospace firms understood that it might take five years for this kind of work to become profitable and that the studies generated valuable experience, many underestimated the problems of developing the new research market, especially in convincing the legislature to fund additional work. Nonetheless Space General and Aerojet-General received second contracts from the state of California, although neither was a follow-on to earlier work. All four original contractors and other defense firms have expanded their work in systems analysis to civilian problems, and most are performing work for state, local, and federal governments. Funding levels remain lower than originally envisioned.

The scarcity of follow-on work is due in part to the character of the legislature, the nature of the problems, and the performance of the original contractors. Criticisms of the studies most frequently encountered were cited by Gilmore:

1. The four reports sometimes showed poor knowledge of the subject, as evidenced by incomplete, inadequate, or incorrect data and incomplete searches of the literature.
2. Some recommendations were politically naive or impractical to implement; the phases of implementation or integration were often underemphasized.
3. There was too much emphasis on engineering and not enough attention paid to social and institutional aspects.
4. The four studies did not attempt to identify problems and then to develop methods to solve them. Rather, the contractors attempted to solve complex problems in the nine months allotted—an impossible task. Consequently they failed at both tasks.
5. The contractors provided few alternative solutions. At most, the contractors talked about two or three different programs, but these generally represented different levels of funding. Contractors typically devoted most of their analysis to one solution. Regardless of their merits, these criticisms represented the perceptions of many potential customers in state and federal civil services.

It should be noted that the studies earned praise, especially for (1) their comprehensive scope in approaching the problems and (2) the freshness of their recommendations, as compared to traditional efforts. A good example of this creativity lay in the study dealing with crime and delinquency. A series of overlays provided a summary of socioeconomic variables that showed high correlations with crime. The chart identified, in a graphic manner, the Watts area of Los Angeles as a "hot spot" in advance of the riots of August 1965.

From the state's standpoint, the four studies certainly created local and national publicity—in fact, they stirred international interest. While most of the publicity was favorable, some criticisms from academics and professionals increased with time, as study recommendations were not implemented.

Ida R. Hoos, perhaps the best known and most ar-
ticulate critic of the "California Studies," has stated that the techniques of systems analysis cannot successfully be applied to social problems. In an article published in *Datamation* magazine, Hoos asserted:

the very characteristics which distinguish social from other species of systems render them resistant to treatment that tries to force them into analytically tractable shape: 1. They defy definition "solve" the problems of health or transportation. Consequently, education, employment, or the one which focuses on individual encompasses the shortcomings of other systems, such as health, education, employment, or the one which focuses on individual inadequacy? A definition depends on the point of view and the ideological posture. The system looks very different to the administrator, the recipient, the black power monger, the social critic, and the politician.

2. "Solution" of social problems is never achieved. You do not "solve" the problems of health or transportation. Consequently, where you start and where you stop is purely arbitrary, usually a reflection of the amount of money the government has to fund the particular analysis.

3. Despite the semblance of precision, there are no right or wrong, true or false solutions. Consequently, it is presumptuous to label as wrong anything being done now and right that which looks good on paper. By concentrating on miniscule portions or isolated variables simply because they are quantifiable, the technique may actually lead to results which are irrelevant and inappropriate. Assignment of social costs and social benefits is an arbitrary matter, and even dollar cost/benefit comparison is a matter of interpretation.

A similar though more extensive criticism of the studies appears in Hoos's book *Systems Analysis in Public Policy*. When viewed from the standpoint of technical soundness and political acceptability, the results were mixed. The wide scope of the problems tackled and limits of time and money contributed to their failings.

It is not possible to determine if the studies enabled or hastened administrative reforms in the state government. Prior to the 1966 California gubernatorial elections, there were indications that the studies helped those reforms. With the election of Ronald Reagan, Brown's goals (which had included the use of systems analysis in state management) were no longer considered desirable.

Albert Lipson, now an employee of the Rand Corporation, was director of research for the California Assembly when the "California Studies" were completed. Lipson states that the studies provided broad new perspectives from which to analyze major problems. But the studies were not of lasting benefit to California, in part because the contractors did not provide the state what it needed. Contractors put the bulk of their efforts into solving problems rather than focusing on methods to solve problems. While their solutions may have been excellent (hence the praise of technical method and value received for dollars invested), the state was not prepared to implement them.

Praise of technical content and criticism of political inviability are not inconsistent. The state administration—like most state and local governments—did not have an overall program to analyze policy. Such a program would typically contain political and technical components—both of which have legitimacy in the process of state governance. Within such a framework, the studies could have been valuable. But they had been undertaken merely as an experiment, as a first attempt in using a systematic approach to solve state problems. As a result, there was no plan for what to do with the studies once they were completed. Lipson states that the governor commissioned a team almost as an afterthought to review the studies and "figure out what to do with them." It made little difference whether Brown or Reagan was governor. The state of California did not have then, nor does it have now, a system of decisionmaking within which to fit such research. The "California Studies" remain interesting artifacts rather than useful documents.

Notes

13. Interview, Daniel Luevano, formerly chief deputy director, Department of Finance, state of California, 29 July 1975.
15. Skybolt was an air-to-surface missile developed for the Boeing B-52. The program was cancelled by the Department of Defense because of cost overruns and an unsuccessful test program.
19. Lipman interview.
27. Black and Forman.
30. Gilmore.
31. Beideman, page 266.
35. Lipman interview.
36. Lipson interview.
37. Luevano interview.
38. Lipson interview.