# **Nuclear Power Reactors:**

# **A Study in Technological Lock–in**

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Recent theory has predicted that if competing technologies operate under dynamic increasing returns, one, possibly inferior, technology will dominate the market. The history of nuclear power technology is used to illustrate these results. Light water is considered inferior to other technologies, yet it dominates the market for power reactors. This is largely due to the early adoption and heavy development by the U.S. Navy of light water for submarine propulsion. When a market for civilian power emerged, light water had a large headstart, and by the time other technologies were ready to enter the market, light water was entrenched.

The history of nuclear power generation can be seen as a competition among several technologies to capture the market. This competition, which began immediately following World War II, was eventually won by the light water technology. At a 1982 conference on nuclear power experience a U.S. delegate claimed: "In retrospect, choosing the LWR [light water reactor] was a wise decision. Not only is the LWR used almost exclusively in the USA today, but this type, based largely on technology developed in the USA, is being used for about 80 percent of all the reactors built or under construction in the world today."[1] While an appropriate decision at the time, it now seems that light water may have been an unfortunate choice. One of the interesting features of this history is the belief held by many that light water is not the best technology, either economically or technically. The evidence in support of this belief, while not incontrovertible, is strong enough to support the contention that light water is not the superior technology. This suggests that other technologies should still be present in the market. Light water, however, has taken virtually the entire market.

## COMPETING TECHNOLOGIES

The Stanley Steamer, direct current electricity, and gas graphite reactors were, at one time, considered the best available technology by knowledgeable people.[2] They also share the feature of being technologies that are not used today.

Important in the competition between direct and alternating electric current were changes in the environment in which technologies operated, altering which aspects of the technology were desirable and which ought to be considered "best."[3] Initially, when electricity transmission took place over short distances, direct current seemed to have an advantage, as it was technically better equipped to meet peak loading problems. As transmission distances grew, however, alternating current gained the upper hand, to a great extent due to its ability to transmit at high voltages and then use step–down transformers to lower the voltage for consumers, thus circumventing the problems of voltage loss. Now, however, direct current is making somewhat of a comeback, with very long–distance, very high–voltage transmission. Similar changes have occurred in the case of nuclear reactors, but here they are more clear cut. Everywhere except in Canada, military issues were the first to be considered—in France and the United Kingdom weapons–grade fissionable material was in demand; in the United States naval propulsion was the main application. When these demands had been relieved or were no longer so pressing, civilian power emerged as the main consideration, and the important characteristics of reactors became cost and safety. After a market for civilian nuclear power was established, these concerns remained in the forefront. Very important in the development of nuclear power, though, was the early interest in military applications. The effects which followed from the military's definition of "best" have been felt ever since.

One part of the explanation for the demise of the Stanley Steamer early this century was the reluctance on the part of the Stanley brothers to adopt high volume manufacturing.[4] Another lies in what Brian Arthur refers to as "historical small events." The steam car fared poorly in important races against petrol cars, and at a crucial time there was an outbreak of hoof and mouth disease in the northeastern United States. This closed the horse troughs which were used to refill the boilers of steam cars. The outbreak lasted six months in 1914, long enough to do irreparable damage to the reputation of the steam automobile. Similar events shaped the outcome of the nuclear reactor competition. First, Hyman Rickover was put in charge of the U.S. naval propulsion program in 1946. His preference for light water was central to most of the history that followed. Second, the explosion of the Soviet nuclear bomb in 1949 caused a civilian power project to be rushed forward, before the physicists involved were ready to make a choice among the available technologies, effectively forcing choice of light water.

Finally, direct current and the Stanley Steamer technologies, and gas graphite and heavy water reactors share one further characteristic. They were all new technologies, competing with other new ones, all operating under dynamic increasing returns.

## COMPETING TECHNOLOGIES AND INCREASING RETURNS

Recent theoretical work on competing technologies has focused on situations in which superior technologies can disappear from the market.[5] If technologies operate under dynamic increasing returns (often thought of in terms of learning–by–doing or learning–by–using), then early use of one technology can create a snowballing effect by which that technology quickly becomes preferred to others and comes to dominate the market.[6]

Following Brian Arthur, consider a market in which two types of consumers adopt technology sequentially. As a result of dynamic increasing returns arising from learning–by–using, the payoff to adopting a technology is an increasing function of the number of times it has been adopted in the past. Important with regard to which technology is chosen next is how many times each of the technologies has been used in the past. Arthur shows that if the order of adopters is random (that is, the type of the next adopter is not predictable) then with certainty one technology will claim the entire market. He also shows that both technologies have positive probability of dominating. Thus the market can get locked into an inferior technology.[7]

In this model it is assumed that the future payoffs to a technology are well known.[8] Typically, however, when a technology is introduced its future payoffs are not well known. Though it is safe to assume that payoffs will increase with use, the degree of improvement is often difficult to predict. Thus a second type of learning common to new technologies is learning about the payoffs. As a technology is used more and more, the uncertainty about its benefits is reduced. This feature has been modeled as a multiarmed bandit which allows explicit recognition of two effects of every adoption: the adopter receives an immediate payoff; and more information is generated about the inherent “goodness” of that technology.[9] This model shows that even if there is a powerful central authority managing these two features optimally, the results of the earlier model remaine: one technology takes the entire market; and each technology has a positive probability of being dominant. An inferior technology can dominate the market if when first used the inherently superior technology's payoff causes the decision maker to lower his estimate of how good it "really" is. As a consequence he switches to the other technology which may produce results good enough that the estimate of its value is not lowered. Because the superior technology is not being used, it cannot prove its superiority or advance along its learning curve. If the results of the inferior technology are good for long enough, the decision maker will eventually have very strong beliefs that it is better than the first technology. Thus he will never switch back to the initial, superior technology, and the inferior technology will dominate the market. This mechanism operates a fortiori in the absence of a central decision maker.

Both types of learning—learning–by–doing and learning–about–payoffs—were present throughout the history of nuclear power, and so theory predicts that one technology, not necessarily the best, would come to dominate the market. Theory also suggests that events early in the process can be crucial in determining the long–run outcome. This seems to have been the case with nuclear power. The early choice of light water for the U.S. naval program resulted in considerable learning about this technology very early in the competition. When the push for civilian nuclear power emerged in the early 1960s light water was well advanced along its learning curve while the other technologies were late entrants which failed to catch up.

## LIGHT WATER, HEAVY WATER, AND GAS GRAPHITE

Nuclear reactors are classified by two of the materials used in their construction: the coolant used to transfer heat from the reactor core; and the moderator used to control the energy level of the neutrons in the reactor core.[10] In a light water reactor both coolant and moderator are light water—$H_2O$. In a heavy water reactor, both are heavy water —$D_2O$.[11] In a gas graphite reactor the coolant is a gas, usually helium or carbon dioxide, and the moderator is graphite. These three types of reactor—light water, heavy water, and gas graphite— while not the only technologies used or feasible, were the most extensively developed as competitors in the nuclear power reactor market.

There has always been doubt as to the superiority, both technical and economic, of the light water reactor.[12] It is difficult to document the claim that light water is inferior in an ex post sense—light water may be relatively good now but had a different technology dominated, we would have an even better reactor. Nonetheless, there are indications that this hypothesis is true. In the fifties, following a debate on the relative merits of enriched uranium (light water) and natural uranium (heavy water and gas graphite), the journal Nucleonics stated that "to the observer of this debate it seems that enriched reactors must rely heavily upon their development potential to do much better than match the power costs of natural uranium systems."[13] Further, the cost estimates made throughout the fifties, detailed later, by no means pointed to light water as the most efficient technology.

Both the gas graphite and heavy water reactors have much lower volumetric power densities (the ratio of power output to core volume) than do light water reactors. While this tends to raise capital costs and reduce design flexibility, it also provides a safety advantage. In the event of a coolant loss, the core will provide a much larger heat sink (particularly in the case of the graphite core) and so the temperature transients will be much smaller, giving operators more time to effect an adequate response. The use of a gas coolant also has the advantage of being safe from phase changes with changes in pressure or temperature. Thus under many fault conditions cooling can be maintained in the gas graphite reactor, when it would be lost with liquid coolant technologies. A second, related advantage of gas coolants is that they can be heated to higher temperatures, which gives the advanced gas graphite reactors a higher thermal efficiency than others.

An element of considerable concern during the British debate over the merits of light water and gas graphite technologies was the steel pressure vessel of the pressurized water reactor (PWR —Westinghouse's light water reactor). The safety principle in the PWR was, and still is, that the vessel never comes close to failure. If a crack does happen to reach the critical size (much smaller than the thickness of the vessel), however, it can grow at speeds up to the speed of sound. There would be no time for reaction. To manufacture a vessel sufficiently free of flaws to be safe from this problem requires very high technology manufacturing abilities, which are beyond the capabilities of many countries and were beyond most countries in the fifties. Both the Canadian heavy water reactor, the Candu, and the second–generation British gas graphite reactor, the AGR, avoid this problem through systematic redundancy. The Candu uses many pressure tubes rather than a single vessel. The failure of a single tube is not critical and gives warning of other potential failures. This makes Candu less prone to meltdown due to coolant loss. The AGR uses a prestressed concrete pressure vessel. There is considerable mechanical redundancy in the system of steel load–bearing cables. Cables can be replaced individually, and again, the failure of a single cable is not fatal and gives warning of other potential failures.

In terms of operating experience, light water has not been significantly better than the other technologies in spite of having logged many more reactor years—an order of magnitude more than heavy water and three times more than gas graphite. While occupational radiation exposure with light water has been approximately equal to that of heavy water, it has been more than 10 times that of the British gas graphite reactors. The annual load factor of a reactor is the ratio of the total amount of power produced in a year to the amount it would have produced had it operated at full capacity, never shutting down, throughout the year. This is the standard measure of reactor availability. The average annual load factors of light water and gas graphite reactors have been approximately equal at 63 percent. Heavy water reactors, however, have had an average annual load factor of 73 percent.[14] This difference is due in part to the on–load refueling capabilities of the Candu, which have been adopted for the AGR.

Hugh McIntyre estimated that the heavy water Candu reactors at Pickering generate power at about 75 percent of the cost of the light water reactors of equivalent size at the Zion 2 generating station in Illinois.[15] This is consistent with analyses done by Ontario Hydro, which suggest that if Ontario Hydro had a mature light water reactor program, the costs of nuclear electricity would be 20 to 25 percent higher than with the current heavy water systems.[16]

There is considerable evidence, then, that other technologies have inherent advantages over light water and that with equivalent amounts of development and use might well have proven to be better.[17] While it is not possible to document definitively that light water is an inferior technology, it seems clear that the dominant position held by light water cannot be due to a unanimous belief in its technical and economic superiority.

## THE DOMINANCE OF LIGHT WATER

At the 1955 Peaceful Uses of the Atom Conference in Geneva about 100 different reactor types were judged not obviously impractical. In 1958, at the second Geneva conference, only about 12 types were seriously considered.[18] In the late 1950s the U.S. Atomic Energy Commision (AEC) was doing research on several different types of reactors, while the United Kingdom and France were working independently on gas graphite reactors and Canada was working on heavy water reactors. By 1960 serious research had been done or was being done on about a dozen reactor types. Of these technologies, six have been used in generating stations (one, the light water graphite reactor, is used only in the Soviet Union), but Irwin Bupp and Jean–Claude Derian stated that by 1975 there were only two distinct reactor types in the marketplace—the light water, basically of U.S. design, and the Canadian Candu, a heavy water reactor.[19] Indeed, in 1986 of the 101 power reactors under construction in the world (excluding the Soviet Union), 81 were light water. Of the 56 planned but not yet under construction, 48 were light water. Light water has taken the lion's share of the world reactor market.

The first reactor to be connected to a power grid was the gas graphite reactor at Calder Hall in the United Kingdom in August 1956. The second was a light water reactor at Shippingport, Pennsylvania in the United States in December 1957. In the very early days of nuclear power, gas graphite had a small advantage over light water in terms of number of generating stations, but light water was rapidly accumulating experience through its use by the U.S. Navy.

In the early 1960s light water began to be commercialized. Under the 1958 Euratom accord and the 1954 Atoms for Peace program light water was introduced to Europe and was quickly accepted by those countries not having indigenous reactor programs. U.S. utility companies began a serious move toward nuclear power in the early 1960s and had ordered 18 reactors by the end of 1965. All of them were light water. About this time France was beginning to have doubts about the economic viability of gas graphite and in 1969 abandoned it for light water. By 1970, only two of the major consumers of nuclear power, Canada and the United Kingdom, had not chosen light water as the technology on which to base their nuclear generating capacity. Canada brought the first full–scale Candu reactor on line in 1967, but by then it was a late entrant into the market. It continues to be the only reactor used in Canada but has not had a big impact on the world market. The United Kingdom, by contrast, entered early with a gas graphite technology. The second–generation reactor was plagued with problems, however, and in 1978 the United Kingdom switched to light water. Canada remains the only country marketing a technology other than light water. Figures 1A and 1B illustrate the progressive dominance of light water in the power reactor market between 1957 and 1983.

## INCREASING RETURNS IN NUCLEAR POWER

"For a range of products involving complex, interdependent components or materials that will be subject to varied or prolonged stress in extreme environments, the outcome of the interaction of these parts cannot be precisely predicted."[20] For these products, Nathan Rosenberg argues, learning–by–using is very important. Nuclear power reactors certainly fall into this class of products. When introduced, the technology was very complex and unlike any then in use. The consensus in the 1950s and 1960s was that learning–by–using would be very important.

The feeling that costs of nuclear power would fall with experience is evident throughout the proceedings of the 1955 and 1958 conferences on the Peaceful Uses of the Atom. Christopher Hinton, one of the British delegates, noted that it "is common experience that the cost of prime movers [primary power sources] falls with the passage of time and growth of techniques." He gave details of the dramatic capital cost reductions experienced by land–based oil engines and by steam engines and remarked: "I am quite certain that in nuclear power that same pattern will be followed."[21] This spirit pervaded the proceedings of those two conferences.

In a 1962 study the AEC claimed that the cost of electricity generated by light water reactors had fallen from 50 mills per kilowatt–hour (kWh) to less than 10 mills per kWh between 1958 and 1962.[22] Even critics of the cost estimates for nuclear power accepted the belief "that 'learning effects' would help reduce costs in the early years of nuclear plant construction."[23] The four reactor units installed at the Pickering generating station near Toronto provide evidence. For the first unit, the time elapsed between going critical and generating full power was 91 days. For the second unit this time was cut to 53 days; the third and fourth units were 18 and 12 days, respectively.[24] As the designs of these units were virtually identical it seems appropriate to ascribe this improvement to learning.

A simple examination of generating–cost data would not provide evidence of learning. While one would expect learning to drive costs down over time, there are several factors which have applied upward pressure. The early generating stations were sold on a turnkey basis, which amounted to a very large discount on the capital cost for the utilities.[25] Thus the cost to the utilities of generating power for 13 of the first stations were artificially low and did not represent true costs. In addition, increased concern with safety over time has resulted in more stringent regulation which has raised costs. For these and other reasons, the cost of nuclear energy, in spite of any learning that might have taken place, has not declined over time. Econometric studies, however, indicate that learning has been important in nuclear reactor technology in several ways. Paul Joskow and G. A. Rozanski estimated learning both by operators and by suppliers of power stations.[26] Their concern was with load, or capacity, factors. In their model any particular plant has a maximum achievable capacity factor, which they call its asymptotic capacity factor. When a utility begins to operate a plant, the operators spend several years "working the bugs out," and the annual capacity factor rises, approaching the asymptotic capacity factor. This is the first type of learning. The second type of learning has to do with the suppliers of nuclear generating stations. As it gains experience, a supplier is able to build plants with higher asymptotic capacity factors—plants of higher quality. Using data on 72 reactors that began operation before December 1975 Joskow and Rozanski found that there "is evidence of an industry learning curve, with technological improvements increasing ultimate [asymptotic] capacity factors of new plants at a rate of about 5 percent per year." [27]

W. E. Mooz found that doubling the number of plants built by an architect–engineer (that is, a firm such as General Electric [GE] or Westinghouse) reduced construction time by about 10 percent and total capital costs by about $55 per kilowatt, or about 10 percent.[28]

Martin Zimmerman's study of the early stages of commercialization of nuclear power in the United States found that "learning–by–doing associated with the first one or two plants was … substantial."[29] Moreover, there was a second type of learning. Learning–about–costs reflects the fact that the benefits accruing to users of a new technology are not well known until the technology has had considerable use. This idea is central to the multiarmed bandit model of technology choice described earlier. Zimmerman found that learning–about–costs was also important in the early reactor market.

There is a form of increasing returns from learning common to any technology competing in the research and development stage of a product's life. In the presence of discounting, a technology that is marketable earlier is of more value than one that takes longer to bring to the market. Thus simply working on a technology increases its value by bringing its completion date closer and increases the incentive to do further work on that technology. This was a factor in the dominance of light water.

It is occasionally suggested that network externalities are also important in nuclear power. The network in this case has to do with information. Information about operating performance, appropriate accident response, and safety regulations can be passed among users of the same technology. This was seen (at least in retrospect) as a key factor in the explanation of the Belgian and Swedish decisions to adopt light water: "The best counter measure against technical problems is to have a production system which is common all over the world…."[30]

Nuclear reactor technology presents a case of a technology subject to strong increasing returns and early uncertainty about the level of its payoffs. There were, and still are, dynamic increasing returns, largely learning economies, particularly in the research and development and early commercialization stages of the technology.[31] Economic theory suggests that the history of this technology will exhibit several characteristics: a tendency for the market to lock in to one of the technologies, not necessarily the best one; early tilting of the process toward one of the technologies; this tilting may be caused by events, which at the time did not appear to be crucial to the coming history; and finally, early inability to see (without the benefit of hindsight) which of the technologies will eventually dominate.

## HOW DOMINANCE OF LIGHT WATER CAME ABOUT

In 1958, after three years of negotiations, six European countries signed the Euratom accord. Euratom was to be an intercountry agency whose mandate was to develop European nuclear power.[32] In 1957, prior to the signing of the accord, A Target for Euratom was written, recommending that Euratom cooperate with the U.S. nuclear reactor programs. That the three prominent European authors advocated close cooperation with the United States provided a strong challenge to the view then current in Europe that British and French gas graphite technologies were the most advanced.[33] Cooperation with the United States, of course, meant embracing light water. This embrace was tightened in late 1958 when the Euratom High Commission signed an accord with the U.S. government which proposed that one million kilowatts of nuclear generating capacity be built. These plants were to be built under U.S. patents, and, as it turned out, largely by the European subsidiaries of Westinghouse and GE. Under this agreement the United States was to provide (tied) technical and financial aid, and indeed this was the source of half of the Euratom budget for research and construction.

The first reactor built under the auspices of Euratom was at Garigliano, Italy, and initially both British gas graphite and light water designs were considered. The choice of light water was another serious challenge to the view that gas graphite was the more advanced technology. "For the first time in Europe, light water reactors achieved technical respectability…."[34] The three plants built under the auspices of the U.S.–Euratom agreement contributed crucial momentum to changing European views about the viability of light water. The final nail in the coffin of European gas graphite technology, however, was the apparent breakthrough signaled by the bandwagon market in the United States.[35] By the mid–1960s light water had become the technology of choice within Europe.

There are two noteworthy features of this period in Europe. The first is the attempts of a central authority, Euratom acting in concert with the U.S. government, to steer the adoption process. Financial aid and technical assistance lowered the cost of developing and using light water, improving its status relative to gas graphite.[36] This was enough to provide light water with a significant entry into both the European consciousness and market.[37] The second feature has to do with uncertainty. In 1960 it was still not clear which of the viable technologies—gas graphite or light water—was preferable. Three events—A Target for Euratom, the Garigliano decision, and the bandwagon market—were all interpreted in Europe as evidence of the inherent superiority of light water.

Before the Euratom accord the European reactor story was English and French. Technology choice for both countries was, to a large extent, influenced by military considerations. The refusal of the United States to share uranium enrichment technology forced both France and the United Kingdom to pursue natural uranium technologies. Both countries felt the need to develop an atomic bomb, and both countries, through the Manhattan Project, had had experience with gas graphite. This was the obvious initial choice for their civilian power programs.

The only first–generation reactor pursued by the Commisariat à l'Energie Atomique was gas graphite. As nuclear power began to be commercialized in the 1960s, French industry and the Electricité de France (EdF) raised concerns over export possibilities. As remarked above, network externalities were thought to be important in the reactor market. One of the concerns of a reactor importer is to be part of a large information network and so prefers to import a commonly used technology. For good reason, EdF feared that if France became technologically isolated, the potential export market would rapidly disappear. In addition, the Garigliano decision and the U. S. bandwagon market were both seen as evidence supporting the view that light water was economically superior to gas graphite. A third economic issue was that the relative costs of fuel had been changed by the U.S.–Euratom accord. Enriched uranium was now available and at subsidized prices. Thus the fueling costs of light water reactors (which needed enriched uranium) relative to gas graphite reactors (which used natural uranium) was significantly improved. The light water arm of the multiarmed bandit appeared, judging by the actions of others, to be having very good results.

These considerations were countered by the desire to retain an indigenous technology, something favored by French President Charles de Gaulle. When he died, however, the tide turned, and in 1969 the government announced that France would no longer pursue the gas graphite technology. When France joined Euratom in 1957 it had hoped to have the French technology adopted as the European standard. This did not happen, and the French nuclear program, one of the most successful in the world, is based almost entirely on the light water technology.

The history of nuclear power in the United Kingdom looks very much like a multiarmed bandit, as first one technology and then another was tried and discarded, occasionally being picked up again later.[38] Development resources were shifted among technologies, depending upon beliefs about the viabilities of the different technologies.

For reasons similar to those relevant in France, there was an early commitment to Magnox, a gas graphite reactor, for the first generation. For the next generation three technologies were actively considered in the late 1950s—heavy water, gas graphite, and breeder reactors. Significantly, as part of the early decision to concentrate on Magnox, plans to build a prototype heavy water reactor in 1953 were shelved. Early results with Magnox were good, however, and so the high–temperature gas reactor (HTR) was given high priority. In 1959, though, the HTR was shunted aside to make room for the advanced gas–cooled reactor (AGR), which was seen as technologically intermediate between Magnox and the HTR. To develop the HTR an international project, Dragon, funded by the United Kingdom, Euratom, and other European countries, was organized in 1959.

For the first reactors of the second generation gas graphite was again chosen in 1965. Heavy water was not yet sufficiently developed, no doubt due in part to the 1953 decision, and light water was thought inferior in terms of safety and long–run development potential. The second–generation gas graphite reactors, the AGR, suffered serious failures. This version of the gas graphite technology was much more expensive than had been anticipated, and the problems of scaling up a 32 megawatt (MW) prototype plant to a full–scale 600 MW generating station proved more difficult than was expected. This resulted in a shift away from gas graphite to heavy water, at least until more advanced technologies appeared. But the decision in 1974 to make this shift for the short run, by creating a large demand for resources to develop the heavy water reactor (SGHWR), effectively ended the long–run prospects of the HTR. "Thus the HTR, the one reactor favored by virtually everybody in the early seventies, was the one decisive casualty of the 1974 decision."[39] The problems of the British heavy water reactor seem to have been generated by lack of experience.[40] Research on this technology had for two decades been shunted aside in favor of work on the gas graphite technology. This was not at all surprising, but to make matters worse, light water had been the subject of massive amounts of research and development over those two decades. When the time came in the United Kingdom to move away from the trouble–plagued AGR, there were two options: heavy water, which would need considerable development before it was ready for commercial use; and light water, which could be used immediately.[41] Finally, in 1977 light water was chosen.[42]

Canada has pursued a single technology, namely heavy water, throughout its nuclear program. There was no desire for nuclear weapons, there was an abundant supply of hydro–electric power, and the security concerns of the United States were not present in Canada. These three factors allowed Canada to proceed at a slower pace, while other countries were forced to adopt strategies which would produce nuclear technology quickly, . At the beginning of the bandwagon market, in 1962, five years after Shippingport, the first commercial heavy water reactor was brought on line. As a small, 22 MW reactor, it was a prototype rather than a serious competitor in the power reactor market. The first–full scale heavy water reactor, a 206 MW Candu brought on line in January 1967, was only the fourth commercial heavy water reactor in the world. (All of the others were designed to produce less than 55 MW.) By this time there were 10 commercial light water reactors in service, four of which were greater than 100 MW. The second nonprototype heavy water reactor was brought on line in April 1972.[43] By this time there were 27 full–size light water reactors in commercial use outside Canada. Though heavy water is the only technology used in Canada and has been exported, mostly to middle income countries, it has not been a large presence on the world market. In this it exhibits the problems associated with a late entrant in an increasing returns process.

During the late forties the primary concerns of the AEC were military. All branches of the Armed Services were interested in nuclear energy, and their projects were being undertaken at several different national laboratories. The high priority given to military tasks meant that there were few resources available for the study of civilian power reactors. In April 1951 Lawrence Hafstad, the AEC director of Reactor Development, wrote that "the cost of a nuclear power plant is essentially unknown. We have never designed, much less built and operated, a reactor intended to deliver significant amounts of power economically." [44] In this aspect, early developments in nuclear power resemble the early stages of a multiarmed bandit—many arms seem feasible, very little is known about the payoffs of any of them, and resources are devoted to reducing this uncertainty.

During the forties and early fifties the AEC was engaged in several reactor projects. While GE's intermediate breeder reactor was the only project aimed specifically at civilian power, four of the technologies under study were important to its future development.[45] In the early fifties, though, the demands of the military were gradually being met, and the AEC began to evaluate the economic prospects of various reactor technologies. This went on throughout the decade. One of the first analyses was made by a group of firms, between 1951 and 1953, on the basis of which the AEC chose four technologies for further development.[46] These industry teams concluded that economically competitive nuclear electricity was a long way off, but that given the state of development of the various reactor types, the light water reactor promised the cheapest electricity.[47]

Cost estimates presented at the first Geneva conference in 1955, however, told a different story. Using data presented at this conference J. A. Lane made cost estimates for various reactor types, under uniform assumptions about prices and operating conditions.[48] He concluded, using the lower bound of his range of estimates, that by far the cheapest electricity, 4.7 mills per kWh, would be produced by gas graphite reactors. The next cheapest, 6.3 mills per kWh, would come from the aqueous homogeneous reactor, although that reactor posed many technical problems, particularly when compared to gas graphite. Water reactors, both heavy and light, were expected to be relatively expensive. The lowest cost estimate for a light water reactor was 14.7 mills per kWh.[49]

Because the AEC was prohibited from building and operating full–scale power plants by itself it was committed to involving industry in the development of nuclear energy, and in September 1955 issued an invitation to industry to build demonstration power plants. In response seven proposals were submitted, each suggesting a different reactor type.[50] Clearly there was no consensus about which type of reactor was best.

In 1957 Project Size–Up was commissioned. One of the goals of Project Size–Up was to compare the light water reactor at Shippingport, the first nuclear generating station in the United States, with Calder Hall, the gas graphite reactor which had gone on line in the United Kingdom a year earlier. The study found that if both had been built in the United Kingdom, the gas graphite reactor would have produced electricity at a significantly lower cost than would a light water plant (8.0 mills per kWh as opposed to 13.1 mills). In the United States, however, gas graphite would still have been less expensive but the difference was considerably less pronounced (17.9 versus 19.6 mills per kWh).

At the same time, a formal debate was sponsored by the journal <u>Nucleonics</u> about the relative merits of enriched and natural uranium reactors.[51] The conclusion of the debate was that it was by no means clear that enriched uranium reactors, which the AEC was heavily backing, were inherently superior to natural uranium reactors. It appeared "that of the design concepts conceived so far, none makes an economic advantage for the enriched uranium reactor a foregone conclusion."[52]

Throughout the fifties comparisons of the various reactor types were continually being made, based both on engineering studies and on the performance of the few existing plants. By no means, however, had they found the light water technology superior to other technologies. Indeed, in 1954 Alvin Weinberg declared that "the choice of water cooling and moderation for PWR [the Shippingport reactor] was dictated by the requirement that the reactor demonstrate reliable nuclear power rather than cheap nuclear power."[53] Interestingly, he suggested that possible improvements on the Shippingport design (made possible by learning by using) include using heavy water instead of light water as coolant and moderator. Many arms of the multiarmed bandit were examined during the fifties, but there was no concensus as to their relative merits. Nonetheless, one arm—light water—was adopted by a major player, the U.S. Navy.

## THE ROLE OF THE U.S. NAVY

The duration of underwater operation of conventional submarines is severely limited because they are forced to run on batteries when submerged. By the end of World War II the U.S. Navy was concerned with this problem and saw nuclear propulsion as a possible solution.[54] Captain Hyman Rickover, in charge of the Navy's new nuclear propulsion program, wanted to produce a nuclear submarine as quickly as possible.

In Rickover we see one of Jonathan Hughes's vital few, someone who was crucial to the development of an innovation.[55] To a very great extent his was the voice that mattered when it came to technical decisions within the Navy's propulsion program. His commitment to pursue nuclear submarines meant that nuclear power technology (in addition to nuclear weapons) would be developed quickly after the war. His preference for light water caused it to be the only technology available when a civilian power reactor was demanded immediately in 1949 by "national security." By pulling General Electric into light water technology he effectively prevented the company from developing any other technology and set the stage for its battle with Westinghouse. In effect, the history of nuclear power in the United States follows on the work of Rickover in the 1940s and 1950s. His contribution came at a crucial time. Before anyone else was prepared to make a commitment to any particular technology, he did. He forced his project to be successful and in so doing gave a sufficient lead to light water. The backers of light water power reactors were able to use this advance along the learning curve and the dynamic increasing returns inherent in the technology to capture the market.

After spending several months at the Oak Ridge National Laboratory in 1946, Rickover was convinced that enough was known to build a prototype reactor. He felt that light water was the technology he wanted, but in 1946 there was certainly no consensus among the physicists that it was the best. They felt that much more study was needed before a sensible choice could be made. Harold Etherington, head of the Naval Reactor Division at Argonne National Labs, was still conducting studies of six reactor types in 1949. His preliminary study of light water (the first that he completed) indicated that there were no insurmountable problems in using this technology for submarine propulsion.[56] Rickover, too, was aware that many technologies were feasible and had arranged to have several laboratories working on various aspects of gas–cooled, liquid–metal–cooled, and sodium–cooled systems, in addition to the Westinghouse work on light water. Diversity notwithstanding, Rickover was determined to build a reactor as quickly as possible. To this end he got a letter from a reluctant Walter Zinn, the director of the Argonne laboratory, stating that on the basis of existing knowledge, light water seemed to be the most promising. This was enough for Rickover. He was able to get approval for Westinghouse to build a prototype submarine reactor on land.

This prototype, known as the Mark I, was tested in early 1953, and its successor, the Mark II, was installed in the submarine Nautilus. The Nautilus was launched in early 1954 and had no major problems in its sea trials. Performance of the first two nuclear reactors made the light water arm of the multiarmed bandit look very good.

During the time that Westinghouse was working on the Mark I and Mark II, technical problems had forced General Electric to abandon its civilian reactor project and turn its energies to its own naval reactor, the Mark A, a liquid–metal–cooled, beryllium–moderated reactor. The Mark A was successfully tested in June 1955, but as it continued to be used, problems developed. The second nuclear submarine, the Seawolf, was launched in July 1956 with the GE Mark B as its propulsion unit. Problems with this reactor were so severe, however, that late in 1956 Rickover had it removed from the ship and replaced with a Westinghouse light water reactor.

The competition with regard to submarine reactors was over. The initial competition took place on paper as Etherington and others studied the feasibility of various coolants. Rickover decided in favor of light water. In the second competition between actual working reactors, the problems with the Mark B caused Rickover to decide against liquid metal for submarines. This decision effectively spelled the end for liquid–metal–cooled reactors.

This was not the end for General Electric in the reactor business, however. While working on the Mark A and Mark B, the company had also been developing the submarine advanced reactor— a light water reactor. Despite problems with this reactor and the feeling that the work could have been done much more quickly by Westinghouse, Rickover kept the project alive. One of his chief motives was to bring GE into competition with Westinghouse in light water technology. Although this reactor was never extensively used as a propulsion unit, it did provide GE with the experience necessary to enter the civilian market with the light water technology.[57]

While the work on submarine reactors was going on, the Navy was also considering the feasibility of nuclear–powered surface ships. The need was less severe than for submarines, but it was felt that a nuclear–powered surface ship would be faster and could stay at sea longer than a conventional ship. The work focussed on developing a nuclear–powered aircraft carrier. Westinghouse had been doing initial work on six different coolants for this reactor, but once again Rickover favored the light water technology.

Since the early 1950s interest had been expressed in a dual purpose reactor—one which would be a prototype for both a large shipboard plant and for a power reactor. Rickover had, until 1954 at least, been successful in vetoing that idea. But throughout this time, two things were happening. The utilities were beginning to show interest in acquiring nuclear power, and the Soviet nuclear program was seen as more and more of a threat to U.S. national interests. In 1952 the AEC had moved civilian power from last to first priority and by 1953 was making plans to build a power reactor jointly with industry.[58] The carrier reactor project had been put on the shelf, for the time being at least, in order to provide funds for the civilian project. Two approaches were available to the AEC for the power reactor. The first was to adopt Rickover's suggestion to transform the carrier reactor into the civilian reactor, with few if any major changes.[59] This would have produced a reliable reactor quickly but would not have provided cheap electricity.[60] The other approach was to take more time and to explore further the work that had been done at the Argonne National Laboratory on light and heavy water moderators and coolants. It was thought that this approach would be far more likely to generate electricity that would be competitive with conventional sources. Hafstad favored the latter approach and was supported by his staff, but Rickover prevailed. The civilian reactor ,"now called the pressurized–water reactor, would follow the carrier reactor design and ...it would be assigned to the naval reactors branch...."[61] This battle was won so handily by Rickover that while still an active Navy officer, he was put in charge of the construction of the first nuclear generating station in the United States. Needless to say, the technology used was light water.

## SHIPPINGPORT AND THE SOVIET BOMB

On theoretical grounds, one might expect that the stronger the increasing returns early in the life of a technology, the faster it will become dominant.[62] Nuclear reactor technology in the 1950s was still very new and very complex. Building a complete power station would involve a considerable advance along what was sure to be a steep learning curve. The first technology in the United States to make this advance was light water.

In the 1940s and early 1950s the AEC had advocated a cautious approach to civilian nuclear power, arguing that much laboratory work was needed before a sensible decision could be made about which technology was best suited for civilian use. It was forced to make an early decision, however, by the National Security Council.

After the second world war the United States believed that if it kept its nuclear knowledge secret, it would enjoy a 20–year monopoly in nuclear technology. This it did, refusing to share either uranium enrichment or reactor technology with its wartime allies. U.S. secrecy explains in part why nuclear programs in the rest of the world focused on natural as opposed to enriched uranium reactors. Under the Atoms for Peace program this changed—the United States was willing to guarantee supplies of enriched uranium and provide other reactor technology.

This change, it seems, was brought about by the Soviet nuclear weapon test. In 1949 the Soviet Union exploded its first nuclear bomb and exploded as well the U.S. dream of a monopoly in nuclear technology. In 1953 the United Kingdom exploded an atomic weapon. There was also evidence that both of these countries were developing civilian power capabilities. It is necessary to remember that in the late forties and early fifties, there was a tremendous faith that nuclear energy could do much good, for example providing inexpensive power to the Third World that would facilitate economic growth. This possibility, combined with the apparent prowess of the United Kingdom and the Soviet Union in the nuclear power field, caused for great alarm in the United States There was a fear that if the world perceived the Soviets to be winning the race for nuclear energy (which the United States had not yet seriously entered), it would draw nonaligned nations, particularly Third World countries, into the Soviet camp. This would do no end of damage to U.S. interests. AEC commissioner T. Murray stated: “Once we become fully conscious of the possibility that power–hungry [that is, energy scarce] nations will gravitate towards the USSR if it wins the nuclear power race, it will be quite clear that this race is no Everest–climbing, kudos–providing contest.”[63] Indeed, Murray thought that permitting the Soviet Union to be first in the race to civilian power would do more damage to U.S. interests than had the Soviet atomic bomb.

Suddenly a new priority had been forced on the AEC. The National Security Council had decided that a strong civilian reactor program was vital to national interests and that it was imperative to get the program going. To this end the Shippingport generating station was built with the idea "to prove American nuclear superiority, not to lower energy costs."[64] Any reactor would do, as long as it was known to be reliable. Clearly the obvious choice was the light water reactor, with which there had been the most experience.

While fear of Soviet superiority led to the choice of the light water reactor for the Shippingport plant, it also led to the desire to have U.S. technology spread throughout the world. As pointed out in reference to Euratom, this resulted in enormous subsidies to Europe to encourage the adoption of American technology. Learning–by–doing was very important in the early stages of the industry, and Europe provided a location in which this learning could take place. If enough plants could be built quickly, U.S. technology would improve rapidly and become the standard for the first generation, until more advanced reactors—breeders or high–temperature gas–cooled reactors, could be developed. Unfortunately, this choice "gave the light water model a head start and momentum that others were never able to match and led the industry to base its commercial future on a reactor design that some experts have subsequently suggested was economically and technically inferior."[65]

In the early 1950s the AEC was given new priorities under which civilian power reactor development became very important. Atoms For Peace, the U.S.–Euratom bilateral accord, and Shippingport were all a result of a new desire that the United States win the race for nuclear power and that its technology should spread throughout the world. Within the country, however, only light water was sufficiently developed to be the standard bearer.

Within the United States, the early years of reactor development were under control of the AEC. Throughout the fifties, based on a continual series of cost estimates and projections, the AEC had a fluid opinion about which technology was best and shifted its research program accordingly. Military demands, however, resulted in considerable work on light water. In 1954, when priorities changed, security decisions demanded an immediate payoff. The potential for using the first generating station as a way of learning about different technologies was sacrificed to the need for a reliable reactor.[66] Because of its experience on submarines, there was confidence in light water's reliability, though not in its ability to produce inexpensive power, even in the long run. At the same time, foreign policy called for the spread of U.S. technology, and again there was a bias toward immediate payoff. This was less conscious than the Shippingport decision, but part of spreading U.S. technology involved building demonstration plants, and only light water was sufficiently advanced.

By 1962 light water had a large head start over all other technologies, with the exception of gas graphite. The latter was being pursued seriously only in the United Kingdom, and its demise was detailed earlier. Good results early on with light water, combined with the problems of other technologies that had been tried, enhanced the relative position of light water in the beliefs of the decision makers. Westinghouse and General Electric, fearing the advent of a new and better technology, adopted a successful loss–leader, pre–emptive strategy. They are effectively the only reactor designers in the United States, and the descendants of their technologies are the only ones currently being built in Europe.

## THE U.S. AFTER 1960

The nuclear power reactor market in the United States the early 1960s can be seen as the tail end of an increasing returns process. If one technology, in advance of its competitors, makes a large movement along its learning curve, the others will be hard pressed to compete, finding it difficult if not impossible to enter the market. The first technology to get significantly ahead of its rivals is likely to dominate the market.

By the early 1960s General Electric and Westinghouse had amassed considerable technical expertise in nuclear technology, almost all of it using light water technology. Their work for the Navy and to a lesser extent their work in Europe had given them enough experience to feel that they had a product for which the market was ready.[67] They thought that there were huge profits to be made in nuclear energy but that a great deal of learning was necessary before the costs would be brought down enough to make it competitive with conventional energy. They had other concerns as well:

> We had a problem like a lump of butter sitting in the sun. If we couldn't get orders out of the utility industry, with every tick of the clock it became progressively more likely that some competing technology would be developed that would supersede the economic viability of our own. Our people understood this was a game of massive stakes, and that if we didn't force the

utility industry to put those stations on line, we'd end up with nothing.[68]

Thus GE and Westinghouse were willing to offer turnkey contracts. They sold 13 plants on this basis and suffered tremendous losses, but by doing so were able to precipitate the Great Bandwagon Market in 1963. In the late 1960s General Atomic attempted to enter the market with a high–temperature gas graphite reactor. By 1975 it had orders for seven power stations, and in 1976 the Fort St. Vrain station came on line. By then, however, all of the other orders had been cancelled, and Fort St. Vrain remains the only high–temperature gas graphite reactor operating in the United States[69]

Within the United States after 1960 we see two firms competing for market share. Using variants of the same technology, they were competing both with each other and with other technologies. They had a tremendous technological headstart over their competitors and worked hard to capitalize on this advantage. In an attempt to make further advances along what they were sure were steep learning curves, they sold early power stations at very low prices. The utilities were very receptive. Light water advanced rapidly along its learning curve, and by the time other technologies tried to compete, it was too late.

## SUMMARY AND CONCLUSION

The history of nuclear power reactor technology has several branches, primarily representing different countries, which slowly intertwine. In essence, the story is one of competition among several technologies, each of which operates under strong dynamic increasing returns, with one coming to dominate the market.

The light water reactor satisfied the U.S. Navy's needs for a small reactor which would be ready for use very quickly. The Navy expended considerable resources on the development of this technology, and as a result, it was the only one available at a critical moment—when national security demanded a nuclear power station. The same national security concerns prompted the U.S. government to force light water into Europe. In the late 1950s and early 1960s three forces came together: questions about the economics of the first generation of gas graphite reactors; large U.S. subsidies of light water in Europe; and claims by the producers of very large decreases in the cost of their reactors.[70] There followed a rash of orders in Europe and the United States, a significant advance along the learning curve, and, equally important, an apparent reduction in the uncertainty about the benefits of light water. This was enough to push virtually the whole market into light water and by 1969 Canada and the United Kingdom were the only holdouts.

For many years the United Kingdom was determined to use its own technology. Throughout the 1970s, however, there was ongoing debate about which technology to use for its secondgeneration reactors. Both gas graphite and heavy water were chosen and pursued. Both presented technical problems, however, and it became clear that the development of either would be very expensive. Since light water had been thoroughly developed elsewhere, the United Kingdom finally adopted it.

The heavy water reactor prevailed in Canada, but by the time it was ready for commercial use, light water had been in use for 10 years, and dozens of light water reactors were under construction. Heavy water's late entry into the competition and its lying outside the mainstream of reactor technology explain its lack of export success.

Recent theoretical developments in the area of competing technologies suggest that if increasing returns are strong, one technology will dominate the market, and it is not possible to predict which of the technologies will do so. It is likely, however, that the technology which first makes large advances along its learning curve will emerge dominant. In the three decades since the first nuclear power station, the light water technology has come to dominate the power reactor market. This has occurred in spite of the fact that from its very first use there were serious doubts as to its technical or economic superiority.

Its rise to pre–eminence can be attributed to three things: the choice by the U.S. Navy in the late 1940s of light water for its propulsion program and its subsequent research on that technology; the desire, following the Soviet bomb, for quick construction of a nuclear generating station; and the subsidies given by U.S. government in an attempt to have light water pre–empt other technologies domestically and in Europe. The first two, at the time, were not generally thought to be as significant as they have turned out to be. At the time of Shippingport, light water was considered an interim technology, and it was expected that very soon, other technologies would take its place. These three things combined to give light water a tremendous advantage in terms of development resources and time. When these other, potentially superior, technologies were developed to the point of being marketable, it was too late. Light water was entrenched.

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[1] International Atomic Energy Agency, Nuclear Power Experience, Proceedings of a Conference on Nuclear Power Experience (Vienna, 1983) vol. 1, p. 51.

[2] For other case studies of competing technologies, see Paul David, "CLIO and the Economics of QWERTY," American Economic Review, 75 (May 1985); Morris Teubal and Edward Steinmueller, "Government Policy, Innovation and Economic Growth: Lessons From a Study of Satellite Communications," Research Policy, 11 (Oct. 1981); and S. H. Karlson, "Adoption of Competing Inventions by United States Steel Producers," Review of Economics and Statistics, 68 (Aug. 1986).

[3] See Paul David with Julie Bunn, "The Economics of Gateway Technologies and Network Evolution: Lessons from Electricity Supply History," Information Economics and Policy, 3 (number 2, 1988).

[4] See Brian Arthur, "Competing Technologies and Economic Prediction." Options, International Institute for Applied Systems Analysis, Laxenburg, Austria (1984); and Charles McLaughlin, "The Stanley Steamer: A Study in Unsuccessful Innovation," Explorations in Entrepreneurial History, 7 (Oct. 1954).

[5] For a survey of the recent competing technologies literature, see Brian Arthur, "Competing Technologies: An Overview," in G. Dosi, et al., eds., Technical Change and Economic Theory, (London, 1988). "Superior" here means "inherently superior." Theoretical results indicate that under a variety of conditions, only one technology will survive in the market. Given this result, the superior technology is that which, if it were to be the surviving one, would maximize net benefits from the technology choice process. This is an ex post definition of "superior."

[6] "Technology" here is a generic term. Following Kenneth Arrow: "At any moment of time, the new capital goods incorporate all the knowledge then available, but once built their productive efficiency cannot be

altered by subsequent learning." Kenneth Arrow, "The Economic Implications of Learning by Doing," Review of Economic Studies, 29 (June 1962), p. 157. Technologies improve but particular instances of them do not.

[7] This model is presented in Brian Arthur, "On Competing Technologies and Historical Small Events: The Dynamics of Choice Under Increasing Returns," International Institute for Applied Systems Analysis (Working Paper WP-83-90, 1983); and in Brian Arthur, "Competing Technologies, Increasing Returns, and Lock-In by Historical Events," Economic Journal, 99 (Mar. 1989). It is possible to find sets of parameters and functions such that only one technology is ever used, and so these results will be violated. The results are very general, however.

[8] Many other models make the same assumption. See, for example, Joe Farrell and Garth Saloner, "Standardization, Compatibility and Innovation," Rand Journal of Economics, 16 (Spring 1985); Joe Farrell and Garth Saloner, "Installed Base and Compatibility," American Economic Review, 76 (Dec. 1986); Michael Katz and Carl Shapiro, "Network Externalities, Competition and Compatibility," American Economic Review, 75 (May 1985); and Michael Katz and Carl Shapiro, "Technology Adoption in the Presence of Network Externalities," Journal of Political Economy, 94 (Aug. 1986).

[9] See Robin Cowan, "Backing the Wrong Horse: Sequential Technology Choice Under Increasing Returns" (Ph.D. diss., Stanford University, 1987). The multiarmed bandit is a problem studied in probability theory, characterized as a slot machine with several arms. The arms are assumed to have different probabilities of paying out, and the object is to play the arms one at a time in any order so as to maximize the expected present value of the winnings.

[10] When an atom is split, neutrons are released which bombard other atoms, causing them to split and so creating a chain reaction. The chain reaction generates considerable heat which is used to turn turbines which generate electricity. To sustain a chain reaction there is an optimal speed, or energy level, for the neutrons. By causing the neutrons to travel through particular substances in the reactor core (moderators), this optimal energy level can be obtained. For an easily accessible account of the technology of nuclear power reactors, see Irwin Bupp and Jean-Claude Derian, Light Water: How the Nuclear Dream Dissolved (New York, 1968), chap. 1, fn. 3.

[11] Deuterium is a naturally found isotope of hydrogen. $D_2O$ is found in nature, in the ratio of approximately 1 part in 5,000 parts $H_2O$.

[12] The sources for the following paragraphs are Nucleonics, 15 (June 1957); W. Marshall, ed., "Reactor Technology," Nuclear Power Technology, vol. 1 (Oxford, 1983); Alan Cottrell, "The Pressure on Nuclear Safety," New Scientist (Mar. 25, 1982); David Green, "AGR v PWR: The Debate Continues," Energy Policy, 14 (Feb. 1986); M. Piran and W. Murgatroyd, "Fuelling Costs of Nuclear Reactors," Energy Policy, 12 (Mar. 1984); and International Atomic Energy Agency, Nuclear Power Reactors in the World (Vienna, 1987).

[13] Nucleonics,15 (June 1957), p. 71.

[14] The source for these figures is International Atomic Energy Agency, Nuclear Power Reactors in the World, table 17. A reactor is included in the average for the entire time it is connected to the electricity grid up to 1987. These figures do not control for things such as different regulatory regimes. If the average performance within a country is used as an observation point, light water looks much better, largely due to extremely good performance in Belgium and Sweden, though still not as good a heavy water.

[15] Hugh McIntyre, "Natural-Uranium Heavy-Water Reactors," Scientific American, 233 (Oct. 1975).

[16] G. R. Fanjoy, "Generating Costs From Candu," European Symposium on the Candu Reactor, London (Mar. 1982); and Ontario Hydro, "Ontario Hydro CANDU Operating Experience," NGD-9 (1987). The lower estimate uses the world average load factor; the higher estimate assumes that the annual load factor would be higher under Ontario Hydro management policies.

[17] For more discussion on the merits of other technologies, see Harold Agnew, "Gas-Cooled Nuclear Power Reactors," Scientific American, 244 (June 1981); Alvin Weinberg and Irving Spiewak, "Inherently Safe Reactors and a Second Nuclear Era," Science, 29 (June 1984); and Eliot Marshall, "The Gas Reactor Makes a Comeback," Science, 29 (May 1984).

[18] See Phillip Mullenbach, Civilian Nuclear Power: Economic Issues and Policy Formation (New York, 1964), p. 39.

[19] See Bupp and Derian, Light Water, p. 6.

[20] Nathan Rosenberg, Inside the Black Box: Technology and Economics (Cambridge, 1982), p. 122.

[21] Hinton also added: “Let us remember that the first movement onward from the Bolton and Watt engine was really made by Trevithick when he built his high-pressure steam engine on the Thames, with its cast iron boiler which blew up, killed eight men, nearly ruined him and set back the development of the steam engine by a great many years. We must make certain that we do not do that sort of thing….” United Nations, Proceedings of the Second International Conference on Peaceful Uses of the Atom (Geneva, 1955), p. 368. See also the proceedings of the First Conference.

[22] See Bupp and Derian, Light Water, p. 45.

[23] Ibid., p. 46.

[24] Peter DeLeon, Development and Diffusion of the Nuclear Power Reactor: A Comparative Analysis, (Cambridge, MA, 1978), p. 200.

[25] A turnkey contract is one in which a price is fixed before construction begins, and any unforeseen costs are borne by the designers, in this case Westinghouse and General Electric.

[26] Paul Joskow and G. A. Rozanski, “The Effects of Learning by Doing on Nuclear Plant Operating Reliability,” Review of Economics and Statistics, 61 (May 1979).

[27] Ibid., p. 167.

[28] W. E. Mooz, Cost Analysis of Light Water Reactor Power Plants (Prepared for the Department of Energy, Rand Corporation, R-2304-DOE, Santa Monica, 1978).

[29] Martin Zimmerman, “Learning Effects and the Commercializatioin of New Energy Technologies: The Case of Nuclear Power,” Bell Journal of Economics, 13 (Autumn 1982). He estimates that the completion of the first plant reduces the cost of future plants by 12 percent. Completing the second plant reduces costs further by 4 percent.

[30] International Atomic Energy Agency, Nuclear Power Experience 1, pp.137, 170.

[31] Strong static increasing returns are present as well but are of less interest from the point of view of this article.

[32] At the time, there was a single European reactor technology, namely the French gas graphite. The French saw Euratom, in part, as a way to get their technology adopted throughout Europe.

[33] This report was jointly authored by Franz Estel, German vice president of the European Coal and Steel Community; Francesco Giordiani, former president of the Italian Atomic Energy Commission; and Louis Armand, president of the French National Railroad Company.

[34] Bupp and Derian, Light Water , p. 37.

[35] Particularly important was the Oyster Creek station, announced in 1963. This was an early turnkey plant built by GE which promised power at 4 mills per kWh. This was a decrease of 60 percent from the costs quoted by the Atomic Energy Commision in 1962. The "bandwagon market" refers to the time 1962 to 1965 during which U.S. utilities ordered 13 generating stations.

[36] There is a distinct similarity between the actions of the U.S. government in this role and those of General Electric and Westinghouse in offering turnkey contracts. U.S. government subsidies applied only to reactor varieties tested in the United States. (R. G. Hewlett and F. Duncan, Nuclear Navy, 1946-1962 [Chicago, 1974], p. 135.) This policy gave considerable assistance to Westinghouse and General Electric and their European subsidiries.

[37] The faith in the light water technology displayed by European willingness to abandon their own gas graphite technology could only encourage utilities in the United States to believe that light water was good. The apparent breakthrough in light water, evidenced by the rash of orders in the United States, in turn encouraged the Europeans to continue to use the U.S. technology.

[38] This section draws heavily on R. Williams, The Nuclear Power Decisions: British Policies, 1953-78 (London, 1980).

[39] Williams, The Nuclear Power Decisions, p. 234.

[40] Interestingly, in 1962 this reactor was considered by the Atomic Energy Agency to have better development potential than light water. See Williams, The Nuclear Power Decisions, p. 197. In 1971 it was referred to as "the best of American BWR [a light water technology], Canadian and British technologies." See p. 213.

[41] Ironically, recent experience with the AGR has been very good. In terms of reliability and availability, it has looked better than other technologies since the mid-1980s.

[42] This decision was reconsidered in the 1980s but was not in the end changed.

[43] In 1964 Sweden completed a 10 MW reactor which was shut down 10 years later. In France, in August 1967 a 70MW heavy water moderated, gas-cooled reactor was brought on line. Later in 1967 the United Kingdom brought on line a 92 MW heavy water prototype similar in design to the Candu.

[44] Lawrence Hafstad, "Reactors," Scientific American, 184 (Apr. 1951), p. 43. Quoted in Bupp and Derian, Light Water, p. 32.

[45] The technologies were being studied under the GE project; in Naval work on gas and light water coolants; and in AEC work on graphite reactors and its work on light water.

[46] These were light water; liquid–metal–cooled, graphite–moderated; aqueous homogeneous; and fast breeder reactors. See Mullenbach, Civilian Nuclear Power, p. 131.

[47] Theodore Stern, "Appraisal of Reactor Systems for Central-Station Power Plants," Chemical Engineering Progress Symposium Series, part 1, 54 (Nov. 1954), summarized these studies. The cheapest electricity, 6.4 mills per kwh, would be generated by boiling water, a light water technology. The next cheapest would be a fast breeder, 6.5 mills per kwh, followed by pressurized water, another light water technology, 6.8 mills per kwh. The most expensive was the sodium–graphite technology at 10.3 mills per kwh. Stern noted, though, that in analyses of this sort the difference between 6.4 and 10.3 "may not be out of the margin of uncertainty."

[48] J. A. Lane, "An Evaluation of Geneva and Post-Geneva Nuclear-Power Economic Data," The Economics of Nuclear Power, series 8 (New York, 1957).

[49] In defense of water reactors, their cost estimates assumed plants with relatively small generating capacity, which, given the faith in increasing returns to scale, would appear to put them at a disadvantage.

[50] The types were liquid–metal–cooled, heavy water moderated; gas graphite; graphite moderated, liquid-metal fuel; homogeneous; two variants of light water; and an organic hydrocarbon cooled and moderated reactor. Lane, "An Evaluation of Geneva."

[51] The participants in the debate were J. R. Menke, president of the Nuclear Development Corp., and W. B. Lewis, vice president of Atomic Energy Canada Limited, both of whom spoke in defense of natural

uranium reactors; and Chauncey Starr of North American Aviation and W. E. Shoupp of Westinghouse, both of whom spoke in defense of enriched uranium reactors. See Nucleonics, 15 (June 1957), p. 68.

[52] Ibid., p. 70.

[53] Alvin Weinberg, "Power Reactors," Scientific American, 191 (Dec. 1954), p. 36.

[54] There are two other technologies that overcome this problem. One is the closed cycle submarine, in which diesel exhaust gas is recycled and mixed with oxygen which has been stored in cylinders, and then re-used. The second is a snorkel submarine, in which air for combustion while the submarine is submerged is obtained from a snorkel arrangement which trails the submarine on the surface. After the war, the U.S. Navy was working on all three of these technologies, only one of which has survived.

[55] Jonathan Hughes, The Vital Few: The Entrepreneur and American Economic Progress (New York, 1986).

[56] His other studies were not completed before Rickover had made his decision.

[57] Combustion Engineering had also been drawn into light water by the Navy and developed a reactor for the hunter-killer submarine, Tullibee, which was launched in 1960.

[58] R. G. Hewlett and F. Duncan, A History of the United States Atomic Energy Commission, vol. 2: Atomic Shield, 1947/1952 (University Park, PA, 1969), p. 226 ff.

[59] Rickover did not want to abandon the carrier project in favor of Shippingport. His proposal was a fall-back position in which he could work on a reactor which would provide valuable information for any future carrier project if the current one was put on the shelf.

[60] See Weinberg, "Power Reactors."

[61] Hewlett and Duncan, A History of the United States Atomic Energy Commission, p. 231.

[62] See Cowan, Backing the Wrong Horse, chap. 4; and Rosenberg, Inside the Black Box.

[63] M. Hertsgaard, Nuclear Inc : The Men and Money Behind Nuclear Energy (New York, 1983), p. 25.

[64] Ibid., p. 27.

[65] Ibid., p. 28.

[66] Recall that the Atomic Energy Commission wanted to do more research before building Shippingport but was overridden.

[67] By the end of 1960, 13 nuclear ships had been launched, and a further 33 were under construction. The two firms had completed or begun construction on eight power reactors in Europe and the United States.

[68] John McKitterick, General Electric vice-president for corporate planning, quoted in Hertsgaard, Nuclear Inc, p. 42.

[69] Significantly, three of the six utilities involved had, at the same time, plans to build other generating stations using light water. None of these plans were cancelled, and by 1974 construction had begun on all of them.

[70] Bupp and Derian, Light Water, are also convinced that the current dominance by light water is due to its early acceptance in the United States, and subsequent rapid spread into Europe. They emphasize, however, the way in which reactors were built largely on expectations of future performance. Many reactors were ordered based on the claims of manufacturers that the next, bigger, generation had achieved enormous cost reductions. These claims turned out to be far from true. The degree to which orders (both in the United States and Europe) preceeded experience is astounding. In 1968, for example, the largest light water reactor that had been operating for a year or more was 200 MW. In contrast the mean size of reactor ordered that year was 926 MW (see figure 4-1, p. 73). This sort of advertising (and to be fair, the willingness to accept it) generated enough light water orders, that, again, other technologies were left behind.