



From Military to Early Civilian Applications

An Appraisal of the Initial Success of the Light Water Reactor Technology

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Abstract

The article presents a historical overview of the development path of nuclear technology, from its military application to its civilian start up (Atoms for Peace) and early commercialisation of nuclear power plants. The chief aim is to demonstrate and analyse the commercial exploitation of nuclear energy and the beginnings of the nuclear industry by means of the link with the military research and development and production and its success based on tight industry-government integration. We describe the gradual growth of national nuclear frameworks and of the industry as a result of a combination of exogenous and endogenous factors originating with the military spill-over effects. These factors evolved during the subsequent phases of the technology development following the transfer of technological know-how from military establishments to civilian atomic agencies and the creation of a private industry.

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1 Introduction

This chapter presents a historical overview of the development path of nuclear technology, from its military application to its civilian start up, under the aegis of *Atoms for Peace* and early commercialisation of nuclear power plants. The chief aim is to demonstrate and analyse the commercial exploitation of nuclear energy and the beginnings of the nuclear industry by means of the link with the military research and development and its success based on tight industry-government integration. Military nuclear technology and production issues were decisive not only in the USA, but also in the UK and in France, where fissionable material was indispensable for nuclear weapons.

The gradual growth of national nuclear frameworks and of the industry are described as a result of a combination of exogenous and endogenous factors originating with the military spill-over effects. These factors evolved during the subsequent phases of the technology development, following the transfer of technological know-how from military establishments to civilian atomic agencies (occurring first in the US in 1946, and later in France and the UK in 1954), and the creation of an independent private industry.

The key development stages of military and civilian applications will be analysed chronologically. The primary concern will be the US, British and French experiences, due to their early start and close military ties. In addition to technology development, we briefly describe the agreements, policies and regulations of the US government and the International Atomic Energy Agency (IAEA) which affected the domestic and international marketing of nuclear power plants. Looking at the international framework will allow us to consider the role of the international organisations fostering the development of nuclear power such as the IAEA, the European Atomic Energy Community (Euratom) and the schemes that acted as vehicles for the international sale of nuclear power plants. Afterwards, we look briefly at two national frameworks. Britain receives more attention because initially it was the only country competing with the US in size and government backing in the international market.

The discussion of early military and civilian deployment of nuclear energy will be roughly subdivided into the following stages:

1. Initial military applications characterised by US leadership of the allies who took part in the Manhattan project leading to the A-bomb (Britain, Canada, France and the US), roughly corresponding to 1940–47;
2. Co-existence between military and civilian applications preceding commercial development, characterised by the creation of a national public civilian

Atomic Agency. Knowledge accumulated under the military was transferred to the Atomic Agency, but tight military control was maintained in the choice, implementation, and deployment of the technology. During this stage, basic and applied research leading to reactor prototypes was conducted and several different technologies were concurrently tested with the primary goal of obtaining plutonium for military purposes;

3. Exclusively civilian applications. Here the focus is on the evolution of a specific industrial autonomy and the establishment of the market duopoly by Westinghouse and General Electric (GE). Their marketing policy was articulated through pre-existing and newly established licensing agreements with European countries and Japan.

In analysing the success of Light Water Reactor (LWR) – the American technology par excellence – and its establishment in the world market, we argue that the success of LWR can be explained by examining the interplay of various factors at work in the US market, along with certain exogenous influences in both domestic and export arenas.

The early technological and economic success of LWR technology can be attributed to a rather heterogeneous set of interdependent factors. In this analysis, however, we find it useful to separate these factors and determine which had the greatest impact at any given time. Some of them, like the military spill-over effect, can be considered exogenous to the industry or as a socialisation of its costs. Others, like the industrialisation nurtured under the US Atomic Energy Commission (AEC), can be viewed as the result of a dynamic interrelation between organisational, industrial and institutional factors. Although at these stages, the industry's role was limited to receiving government contracts and procurements and/or working under strict military control, this period marks the beginning of a close interdependence between the military establishment (and later the atomic agencies) and industry that enhanced growth of internal capabilities and nurtured what can be called the military-industrial complex.

2 Early military and civilian applications in the USA²

Early military applications

With the US entry into war in 1942, and amid widespread fears that Nazi Germany was progressing in atomic research for military ends, the American authorities stepped up research on the military application of nuclear physics. In September 1942, the US Army formed an organisation known as the “Manhattan Engineering District” under General Groves. The District’s task was to reorganise work formerly undertaken by the National Defence Research Committee, which was established in 1940, and subsequently part of the office for Scientific Research and Development. The “Manhattan Project” pooled together the best scientists of North America and Western Europe. The programme of the Manhattan District was initially managed by the Army Corp of Engineers, before responsibility was entrusted entirely to the US Army in 1943.

The discovery of Plutonium 239 in December 1940 and its devastating explosive potential catalysed great efforts to build nuclear reactors whose main purpose was the production of plutonium. It should be noted that the military-scientific establishment encountered severe problems in obtaining self-sustaining nuclear chain reactions. In particular, the production of sufficient quantities of uranium and graphite in the state of purity required by laboratory and industrial operations was well beyond that currently available. By 1942, the first chain reaction took place at Fermi’s Chicago Pile-1 (CP-1) using natural uranium as fuel and graphite as a moderator, with a power of 200 Watts.³ This experiment demonstrated the feasibility of using atoms as an energy source, although applications for civilian use were to be a long time in the making.

In fact, a period of strict secrecy was ushered in, during which the atomic project had top military priority which led to a pooling of scientific and financial resources. The construction of additional, larger reactors quickly followed, such as the reactor at Oak Ridge and a second “Chicago Pile”. A third offspring of Fermi’s pile used enriched uranium and heavy water (in place of graphite as a moderator) to produce 300 kW of power. To put it with Wellersten (2017) “virtually overnight, the University of Chicago had become a major wartime contractor”.

Subsequently, several additional plutonium reactors of the so-called “Hanford” type were built under the control of the Manhattan District and under management of the DuPont Company. Natural uranium was deployed in the form of

2 This section draws on my dissertation (Di Nucci 1986), on Sanger and Wollner (1995) and De Wolf Smyth (wd).

3 http://www.atomicarchive.com/History/firstpile/firstpile_01.shtml

rods encased in aluminium, with graphite as a moderator and water as a coolant, while uranium concentrate was obtained from a diffusion plant at Oak Ridge. This work was backed up by scientific research performed at the University of Chicago (Argonne National Laboratories), Ames Laboratories and other universities. The chemistry of plutonium was studied at the University of California in Los Angeles (UCLA) while Columbia University handled the experimental nuclear data central to the uranium technology. Reactor construction and the entire nuclear fuel cycle were characterised by a close interaction and cooperation between scientific and university establishments and supported by industrial groups responsible for the production of key equipment (bound by military secrecy).⁴

This spectacular pooling of resources led to a rapid advance in pure and applied scientific knowledge and in engineering skills as well as innovative production techniques. Increased confidence in the programme's potential paved the way for a special group based out of UCLA to take charge of the design, construction and testing of the atomic bomb. This project, known as the Los Alamos Laboratory, began operation in 1943. At its disposal were minimal amounts of fissionable materials, before more could become available from the first working reactor.

By 1944, Los Alamos had its own reactor for use in research on the A-Bomb. Uranium was present as a solution in the form of uranyl sulphate, rather than in metallic form. The reactor was referred to as the "water boiler". Its explosive properties were rapidly exploited and brought under control, culminating in the successful nuclear test in New Mexico in July 1945. In August 1945, the first uranium 235 bomb fell on Hiroshima, to be followed by a plutonium bomb on Nagasaki three days later.

The transition period

With the end of World War II, it became clear that nuclear energy would open a new era. Under President Truman, the US decided to keep the development of nuclear energy under secrecy and control in the name of national and international security. To ensure this, a domestic regulatory framework was required. It was provided by the May-Johnston Atomic Energy bill of 1945, which advocated military control over atomic technology and information. The bill further underlined the military use of the new technology and confined industrial application within highly restricted boundaries. Against the background of the Soviet hydrogen bomb tests in the 1950s, nuclear weapons remained a highly delicate and divisive political issue. Conservatives feared the loss of US military supremacy while liberals feared nuclear war. The scientific community was similarly divided.

4 See news releases about Argonne's nuclear science and technology legacy, <http://www.ne.anl.gov/About/hn/>

Meanwhile, the countries that had contributed to the Manhattan Project were denied access to the technology, due to the American fear of espionage. This put an end to US-UK nuclear cooperation in 1946, except in the field of uranium ore procurement. While there was no evidence to suggest that the other countries involved in the Manhattan Project could not independently handle the theoretical aspects of nuclear energy, the predominant view was that the US would retain its leadership through its greater experience and sheer weight of human capital, infrastructure, overall organisation, industrial planning and supply. However, the scientific community, including many scientists and engineers who collaborated on the project leading to the bomb, saw the military supervision and control as an unjustifiable interference. The critique and subsequent protest against the May-Johnston Bill led to a compromise in the form of a committee composed of scientists, engineers, industrialists and politicians chaired by Senator McMahon. After many hearings, the committee concluded that nuclear energy was essential for both national defence and industrial growth. It recommended that this development be entrusted to a civilian commission with access to the knowledge obtained through the A-bomb research. The resulting bill went through various amendments before being passed in August 1946 as the "Atomic Energy Act".

The United States Atomic Energy Commission (AEC) was established to nurture and control the development of nuclear science and technology and its civilian applications. The McMahon Atomic Energy Act, signed on August 1, 1946, transferred the control of nuclear matters from military to civilian hands. The AEC was entrusted with the control of the plants, equipment and laboratories which were involved in the production of the atomic bomb. The transfer of the atomic establishment into civilian hands hardly diminished the conflicts between the military and working scientists, a considerable number of which resigned from the laboratories and plants.⁵ The transfer of knowledge, plants and equipment was to be overseen by five commissioners who were approved by the military and the president. Yet, disagreements were rife and the commission sometimes refused to approve the requests made by army officials for exemptions from transfer. When General Eisenhower became president in 1953, the Joint Chiefs of Staff of the armed forces recommended that the president emphasise the superiority of the US stockpile of nuclear weapons, while science advisors recommended a programme called "Operation Candor" to communicate the dangers of nuclear war (Etzkowitz. 1984: 419). The concept of a nuclear industry was then proposed.

5 President Truman signed an executive order to transfer the Manhattan Engineering District on December 31, 1946.

The start of the civilian applications

A civilian nuclear industry was established in part to legitimatise the development of nuclear weapons. Eisenhower's "Atoms for Peace" speech to the United Nations on December 8, 1953, marked the beginning of large-scale US government funding to develop civilian nuclear power plants (Camilleri 1977).

Most applications were developed through the government's national laboratory system, in which Argonne played a key role. The AEC launched the "Power Reactor Demonstration Program" (PRDP), and within this framework a number of various demonstration reactors (light water, gas cooled and breeder reactors) were built.

At the time the AEC was born, the US assets in nuclear energy were constituted by:

1. The Oak Ridge and Clinton Laboratories, working on gaseous diffusion and producing enriched uranium;
2. The Chicago Group, which continued to carry out work on the Hanford reactor but also handled research on the fast breeder reactor (Argonne Laboratories), with General Electric taking over from DuPont. In Chicago, there was also a project using natural uranium and heavy water as a moderator, in addition to fabrication techniques for producing and testing alternative moderators such as beryllium;
3. The Manhattan District, which had also begun studies on various combinations of fuel-moderator-coolant for different types of reactors, in particular the gas-cooled natural uranium reactor deemed feasible for civilian use;
4. The Knoll Atomic Power Laboratory at Schenectady, which had been organised in 1949 under contract for civilian development in the years to come; and
5. GE, to promote nuclear power for ship propulsion, under direct control of the Navy⁶.

Ahead of Eisenhower's "Atoms for Peace" speech, the AEC started considering civilian nuclear power in 1952. By 1953, it was making plans to build a power reactor in collaboration with industry. Plans to develop nuclear-powered surface ships were abandoned in order to provide funds for the civilian project (Cowan 1990: 561).

In 1961, the AEC Development Program was upgraded to include the subsidisation of large scale reactors (400 MWe and larger), in an effort to realise economies of scale and reduce capital costs. In 1962, the Joint Committee on Atomic Energy responded to growing pressures from industry and utilities by specifically allotting

6 A similar project was undertaken at Oak Ridge under the Air Force, the Manhattan District and the Fairchild Aircraft and Engine Corporation's control. Finally shelved in 1961, the project was known as NEPA: Nuclear Energy Propulsion for Aircraft.

\$20 million in subsidies from the AEC to the design, construction and operation of large scale LWRs (Burness et al. 1980: 189).

3 Military spill-over: LWR as by-product of submarine research

The development of LWR technology is intimately connected with military applications. Companies involved in its development are positioned to profit from the economic advantages and scientific know-how nurtured within the military-industrial establishment (Di Nucci 1986, Cowan 1990). Following World War II, Navy submarine's reactors and their operating procedures became the prototype for the most widespread commercial nuclear power plants.⁷

The spill-over effect by the US Navy significantly influenced technological development in the years to come, and military officials played a key role in this new development pathway. Admiral Rickover, known as the "Father of the Nuclear Navy", was put in charge of the US naval propulsion programme in 1946. In May 1946, Rickover, who originally had been assigned to work with General Electric (GE) at Schenectady to develop a nuclear propulsion plant for destroyers, started pushing the idea of nuclear marine propulsion. Subsequently, Rickover became chief of a new section in the Bureau of Ships, the Nuclear Power Division, and began work with Weinberg, the Oak Ridge director of research, both to establish the Oak Ridge School of Reactor Technology and to begin the design of the pressurised water reactor for submarine propulsion (The Economist 2012).

While the earliest studies were performed at Oak Ridge, work was transferred to Argonne in 1948 and development was jointly taken over by Argonne and Westinghouse.⁸ That same year, Argonne's Naval Reactor Division was established. Whereas Argonne scientists and engineers performed much of the early research, design and feasibility studies, Westinghouse improved and implemented the designs, first in the S1W prototype at NRTS, and then in the Nautilus submarine reactor. The first test reactor plant, a prototype referred to as S1W, began operations in 1953 at the

7 The difference between a submarine reactor and a PWR for electricity generation is that they have a high power density in a small volume and run either on low-enriched uranium (as do some French and Chinese submarines) or on highly enriched uranium (>20% U-235). U.S. submarines use fuel enriched to at least 93%. (Wiki)

8 Argonne is a direct successor of the University of Chicago's Metallurgical Laboratory, where Fermi supervised construction and testing of the Chicago Pile 1.

Naval Reactors Facility in Idaho. Bettis Laboratory and the Naval Reactors Facility were in charge of the reactor operation and were managed by Westinghouse.

According to official documents (Argonne, w.d.), researchers faced difficulties in designing a high-efficiency nuclear reactor small enough to fit in a submarine hull and still produce enough energy to drive the vessel. They used high-pressure water to cool the reactor core, a breakthrough in reactor technology. The first prototype, Submarine Thermal Reactor Mark I, was completed in 1953 by Westinghouse. STR Mark II was installed in 1954 in the USS Nautilus, the world's first atomic-powered submarine.

A second type of reactor was installed on the submarine USS Seawolf (SSN-575). It was initially powered by a sodium-cooled S2G reactor and supported by the land-based S1G reactor at the Kesselring site, under Knolls Atomic Power Laboratory and operated by GE. An additional S2G was also built, but never used. USS Seawolf was plagued by super-heater problems and thus the higher-performing USS Nautilus was selected as the standard US naval reactor type. Even though GE's technology was not a success, the corporation gained the experience necessary to enter the civilian market with the LWR technology through its participation in the Navy programme. (Di Nucci 1986; Cowan 1990). The efficient safety and control methods mandated by the Naval Reactor Program were transferred to the civilian market: another notable spill-over from military research.

By 1962, the US Navy had 26 nuclear submarines in operation and 30 under construction. Further development of LWR technology was based on the experience from the naval nuclear programme and on a series of experiments performed using the nine Argonne research reactors (Argonne, w.d.).

The early choice of LWR for the US Navy Program provided for substantial learning about this technology at a very early stage. Thus, by the time the civilian programmes started in the early 1960s, the LWR technology was "well advanced along its learning curve while the other technologies were late entrants which failed to catch up" (Cowan 1990: 545). LWR submarine technology was shared with the United Kingdom, while technological development in France, China and the Soviet Union proceeded independently.⁹

9 Rolls Royce built similar units for Royal Navy submarines and then developed the design further to the PWR-2. The Soviet Union concentrated also on PWR in submarines and never engaged in the development of Boiling Water Reactors (BWR).

4 The establishment of the international atomic framework¹⁰

At the time of the first Geneva Conference in 1955, there were roughly 100 different kinds of reactors under scrutiny (Cowan 1990). Approximately 70% of the development programmes for nuclear reactors were in military hands. However, by the second Geneva Conference, only 12 reactor types were being seriously considered (Mullenbach 1963: 38–39).

At the second conference, negotiations began for the establishment of an International Atomic Energy Agency under the auspices of the UN. Also under way were negotiations for a set of bilateral agreements between the US and other nations for cooperation on the development of civilian use of atomic energy. The US set aside 200 kg of Uranium 235 to assist in international R&D under the aegis of the “Atoms for Peace” programme.

By the end of 1961, 37 bilateral agreements were in effect between the US and other countries and 24 grants were available for the construction of research and experimental reactors as well as laboratory equipment. Though the 1955 Geneva conference was hailed as a breakthrough for the peaceful exploitation of the atom, its outcome was rather limited in terms of transfer of technology and international cooperation. What it did achieve was the legitimisation of nuclear power, inducing an optimism in many parts of the world that a plentiful supply of cheap energy was around the corner. Difficulties with the new technology, especially on the production side, were downplayed or overlooked. As a result of the strict secrecy of the previous military development stage, the industry was not yet in a position to master the technicalities associated with scaling up from the prototype stage to commercial sized plants (Cohn 1997, Di Nucci 1986).

In the years following the Geneva Conferences, numerous international organisations were established with the aim of fostering cooperation between countries. Following the New York Conference on Atomic Energy, the International Atomic Agency (IAEA) was created in 1956. Based in Vienna, its goal was to enhance and increase the contribution of nuclear energy for peaceful purposes. Of the initiatives involving Western Europe, many can be considered as extensions of the Marshall Plan and of the Organisation for European Economic Cooperation (OEEC). OEEC countries gave life to a European Nuclear Energy Agency in 1957, unifying their legal restrictions and nuclear regulations.

10 This section draws heavily on Di Nucci (1986).

Alongside this development, the six countries that formed the Coal and Steel Community set up the European Atomic Energy Community (Euratom) in 1958.¹¹ Though the IAEA was not to substitute for cooperative agreements between countries, this agency was expected to establish safeguards, foster the growth of nuclear energy and the exchange of information and serve as a supply agent for materials, services and equipment. Despite its ambitious aims, the agency achieved limited results. It drew up regulatory procedures for nuclear reactors, but never had the power to implement them, nor did it achieve concrete results in connection with third party liability. Euratom launched an ambitious nuclear programme envisaging 15 GWe by 1967, but this was revised in 1960 to 10 GWe of installed capacity by 1970. In addition to the establishment of four joint research centres, a number of initiatives were adopted within the Euratom framework; the most important of which was the joint programme with the US.¹² This established the terms of cooperation between the US and Euratom member states in nuclear R&D and reactor construction. Notably, US manufacturers willing to participate were then obliged to supply design and cost specifications to Euratom and to set up licensing agreements or subsidiaries within Euratom countries. The latter took place between 1957 and 1960. Although minor in terms of American penetration in the European market (the programme resulted in the sale of only three nuclear power plants, partly backed by the Export-Import Bank), it was of great significance for the transfer of LWR technology to Europe.

The first invitation for proposals on nuclear plant construction was jointly made by Euratom and the US AEC in 1959. This joint programme was decisive for the US industry because it required that proposals for nuclear plant construction include a reactor type on which R&D had already been carried out to an advanced stage in the US. For projects to qualify and be approved, one or more US manufacturers and one or more Euratom member countries had to pay a determinant role in the construction of the nuclear plants. The selected and approved projects were eligible for loans from the Export-Import Bank at preferential rates. The fuel could be purchased by Euratom from the US AEC on a deferred payment basis, while the US AEC provided fuel burn-up guarantees. The Euratom Supply Agency entered into long term contracts with the reactor operators.

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- 11 The signing of the Treaty was preceded by the release of the report "A Target for Euratom" which recommended the cooperation between Euratom and the U.S. nuclear reactor programme. This cooperation can be seen as another vehicle for the penetration of LWR technology, ousting the French and British gas-cooled technology (Cowan 1990, Di Nucci 1986)
 - 12 For details, see Lucas (1977) and the inquiry known as "The three wise men report" leading to the establishment of Euratom.

Given the availability of technical information, the “joint programme” went further than previous initiatives, for it worked exclusively through licensing agreements and joint ventures which allowed European firms to achieve a gradual build-up of nuclear capabilities and to carry out subsequent autonomous nuclear R&D.

5 Other national frameworks

In the late 1950s, the United Kingdom and France were independently developing gas graphite reactors – drawing knowledge and experience from the Manhattan Project – and Canada was working on heavy water reactors. In both European countries, the technological option was also influenced by military concerns. The US’ near monopoly on uranium enrichment technology left France and the UK no other choice but to develop natural uranium technologies for their civilian power programmes. In the following, we analyse the political and technical contexts in these two countries.

Significant emphasis has been laid on certain factors which are the success of the US nuclear framework and technological choice, as compared with other national paths such as the British one. In this context, the work of Burn (1967, 1978) provides a detailed and complete analysis which represented a reference for those advocating the benefits of free market forces for technological development. Burn attributes successes to policies inspired by a mixture of free market criteria and industrial promotion, but hardly considers that the US reactor vendors strongly profited from the R&D and subsidy support within AEC “infant industry” development strategy (Cohn 1997: 75).

In the USA, nuclear fuel and uranium enrichment remained a government preserve and was highly subsidised (Mullenbach 1963), a fact which gave the US industry a kind of artificial competitiveness vis-à-vis other countries that at that time could not hope to match. A questionable feature of Burn’s analysis is his account of the handing-over of the US AEC’s knowledge to the market and the “industrialisation” of the experience matured under the US AEC. Burn (1967) shares the same criticism as Mullenbach (1963) that the technological choice was functional to the possibilities of the national industry and that the US nuclear policy was in some sense subordinate to the interests prevailing in the industry. Our claim, rather, is that while it is true that the American industry displayed internal economies, it is also the case that this was achieved on the heels of a phase in which military targets received absolute priority. Only later was it possible to pursue the needs for a civilian development of nuclear power. The high priority assigned to military targets in the

USA remains therefore one of the chief factors explaining the development. Britain, France and Canada were countries which – like the USA – had a military nuclear experience, but one that began later, was more limited in the extent of its operations and thus lagged behind the USA in terms of its developments and spill-over effects.

Another factor distinguishing the European from the US development – one which Burn (1978) emphasises – is the incubation period provided for nuclear technology. While the US authorities allowed for the parallel development of the most promising projects before the most feasible technologies – in the economic, military and technical sense – emerged in the market, France and Britain ventured into a sort of technological wager which led to the pursuit of single projects to an advanced stage, beyond the point at which they could be easily be shelved in the case of limited commercial and technical success.

The United Kingdom¹³

As in the US, nuclear power in the UK began with the military. In 1941, a team of British scientists established the general feasibility of a bomb design and reactor construction. By 1942, it had become clear that research cooperation with the US would significantly benefit both nations. Once the Manhattan Project fell under a cloud of strict secrecy, however, Britain had difficulties accessing US laboratories and was forced to rely on independent R&D. The US Atomic Energy Act of 1946, with its tight security restrictions, thus effectively deprived Britain of access to the technology following World War II.

A British Atomic Energy Act became effective in November 1946 and allowed for nuclear development under largely similar conditions to those in the US, though without the same harsh penalties for security violations. Responsibility for production, use and disposal of nuclear material was assigned to the Ministry of Supply (MoS). Government authorities established a strictly centralised control over all the activities connected with the development of nuclear energy. In 1948, the Radioactive Substance Act entrusted to the MoS complete authority over the control and use of all radioactive substances, including the regulation of their import and export.

Nuclear power development was pursued by the Atomic Energy Production Division of the Atomic Energy Department of the MoS at Risley. The first scale reactors were built at the Atomic Energy Research Establishment at Harwell in Oxfordshire, which was established in 1946 under the MoS. The reactors were planned as prototypes exclusively to produce plutonium for military purposes. They used natural uranium and graphite as a moderator; they were first cooled

13 This section draws on Burn (1978; 1967) and on Williams (1980).

by air, then by gas. The original plan to have water cooling, as in the US Hanford reactors, was dropped for safety reasons and for the lack of suitable sites (Gowing 1964; Williams 1980). By the end of the 1940s, British efforts had resulted in a plant for the manufacture of uranium, located at Springfield, and facilities for uranium enrichment and the production and separation of plutonium.

In 1948, Britain's Harwell Group initiated a project to study the steam aspects of dual reactors, with the aim of awarding a construction contract to the most successful firm. However, conflicts with the Risley group impeded the project. The main objections were based on the need for plutonium for military applications and the fact that Lord Hinton – who would a decade later become the first head of the newly created Central Electricity Generating Board – and the Risley group mistrusted the industry's reliability (Gowing 1964: 185–190). All the same, data was accumulated at Harwell from feasibility studies that lasted from 1951 to 1953. This resulted in the design of a dual-purpose reactor to be used jointly for the production of electricity and plutonium. With the growing demand for plutonium, the government approved a proposal to build the Harwell-designed reactor in February 1953, a decision that led to the first Calder Hall reactor, known first as Pippa and later as Magnox. It used natural uranium, graphite as a moderator and carbon-dioxide as a coolant. According to Gowing (1964), while there was plenty of support for the LWR option and for later development of Heavy Water Reactors (HWR) and High Temperature Reactors (HTR), the LWR solution was dropped because its potential for being scaled up was not recognised. Thus, what Burn (1967) calls the “Lord Hinton approach” set in, namely a concentration of efforts on the gas-graphite technology with an eye towards fast breeder reactor technology, and, importantly, fissile material production for the UK's developing a nuclear warhead programme. The Calder Hall reactor began producing electricity in July 1956. The work itself was the Harwell and the Risley Groups, since all development of the technology had been fully centralised in government establishments.

In 1954, and in parallel to the change in the US Atomic Act, a new legal framework was established in Britain. The change was less radical than that in the US since it amounted to amending and extending some points of the existing acts in order to establish a civilian atomic energy authority and assign suitable power and liabilities. Unlike the US, there were no special provisions for declassification of information; the 1946 Act had already laid guidelines for an automatic process of declassification for matters of no strict significance for defence purposes. The UK Atomic Energy Authority (UKAEA) was created to embrace both civilian and military atomic activities and to act as a consulting agency on all nuclear affairs. The new agency was entrusted with R&D, including fuel elements, the prototype stage and the phase leading up to the construction of the first commercial plant.

Only at that point was it envisioned that industrial firms would enter in the field and realise projects based on UKAEA R&D results. With the Calder Hall plant in its early stage of development, it was nevertheless decided that this would constitute the grounds for a large scale nuclear power programme. The provisional nuclear power programme was announced in a government White Paper in February 1955 and anticipated the construction of 12 plants with a total capacity of 1,500-2,000 MW by the end of 1965. The first plant was to be of the Magnox type.

The Harwell Group's experience in design, research and preliminary work pointed to the advantages of an integrated system in which the civilian, mechanical and nuclear parts of the plant would be jointly designed. Difficulties arose, however, in developing the industry and in establishing a coordinated approach for design and construction. The industry was handicapped by its virtual ignorance of almost nine years of nuclear growth, and further limited by the lack of a precise framework for collaboration with the UK AEA.¹⁴

The UK AEA retained for itself most of the reactor development and prototype construction; industry was allowed to undertake further design and development in connection with its role in full scale plant construction. Thus, when contracts were awarded to the chosen consortia, the UK AEA acted as a consultant on a turnkey basis and the industrial consortia undertook most of the R&D required to improve the Calder Hall technology. The UK AEA began R&D on other technologies like the advanced gas cooled reactor (AGR), but it simultaneously encouraged industry to take on its own R&D with the aim of contracting successful technologies in the future. Following the Suez crisis, the atomic energy plan was tripled and the power of projected plants was raised to 5,000-6,000 MW by 1966, with £ each plant to be as large as technically feasible with the expectation of reducing costs (Burns 1978). The five plants using Calder Hall Magnox technology were built by five different groups and involved design changes such that each could be regarded as a prototype. The first "commercially" operated Magnox plant was technically modified, at the instruction of the Ministry of Supply to optimise plutonium production for future UK military use, and later export to the U.S military nuclear programme run by the U.S AEC (Lowry 1989). At the end of 1957, the introduction of a new AGR technology was announced. It was based on the Magnox design but used enriched uranium. With this, a second nuclear programme began in 1965 with the contracting of the Dungeness B plant. While the choice of AGR received some criticism, it was preferred to LWR for technical and political reasons. However, the

14 According to Burn (1978: 277-78) some of the consortia were seeking a greater degree of freedom and eventually to take up licensing arrangements with US companies.

emphasis on this technology over all others brought the UK AEA to technological and commercial disaster.

According to Burn (1967, 1978), the commercial failure of the British technology can be attributed to both design and project management. The AGR reflected three fundamental mistakes in decisions made between 1955 and 1957. They were:

1. to have started a nuclear plan exclusively based on the Magnox technology;
2. to have tripled it by 1957;
3. to have limited the subsequent R&D to gas-graphite reactors.

The results of the implementation of AGR technology was to concentrate the industry on the production of systems without a secure future. The public monopoly over R&D was responsible for the excessive rigidity of the structure, which according to the plans, should have been highly dynamic.¹⁵

Although the UK AEA assisted potential buyer countries in obtaining credits extended for five years from the commissioning of the nuclear plant, the only successful bilateral agreements were the two signed contracts with Italy and Japan. These resulted in the sale of a 200MW and a 150MW Magnox plant, respectively. Thereafter, Britain failed to capture any orders on the international market. Officials often justified this failure by alleging unfair competition from the US government, citing the US' preferential loans for construction, artificially low fuel prices, exceptionally good terms for reprocessing the fuel and guarantees backed by the federal government.

France¹⁶

Like Britain and the US, France had a military start to atomic energy development. The early French nuclear reactors were designed and built to produce plutonium. Unlike the US, which attempted to separate civil and military uses of nuclear power, France has never separated the organisation of nuclear energy and nuclear weapons. "This has remained the underlying rationale until today" (Schneider 2008:8).

Following the end of WW2, the Commissariat à l'énergie atomique (CEA) was established as a highly efficient agency regulating the use of nuclear energy. However, the general orientation of the agency, with its strong military bias in R&D, led to the retirement of Joliot-Curie who had been among the pioneers of

15 For a detailed analysis of the policy aspects and the role of the government in the development of AGR technology, see Williams (1980).

16 This section draws on Scheinman (1965), Di Nucci (1986) and Schneider (2008).

the nuclear discovery, but whose political convictions were incompatible with the military emphasis of the CEA.

In 1952, the first 5-year plan for atomic energy was launched by the Secretary of State. It was based on the production of plutonium for military ends by dual purpose reactors. Around the same time, a Commission for the production of electricity of nuclear origin (PEON) was established to liaise with the CEA, the nationalised electric utility *Électricité de France* (EdF) and the industry engaged in the production of nuclear components. In response to General de Gaulle's ambitious pursuit of *grandeur*, the atomic agency objectives became to further the country as a military power by means of atomic weapons and, given its limited internal resources, to free it from dependence on foreign supply and technology. Due to the excessive cost of uranium enrichment plants and to the US ban on the export of enriched uranium, France faced similar limitations as Britain in its choice of moderator, fuel and coolant.¹⁷

Cost considerations ruled out the heavy water option and with it, the need for fissionable material for military purposes. France, like Britain, settled on gas-graphite reactors. The first was built at Marcoule and the plutonium it produced charged the first French atomic bomb, exploded in 1960. And just as in the UK, the first large scale gas-graphite reactors, as Chinon, were presented publicly as civilian, and named EDF-1 and EDF-2 (Davis 1988). Major challenges for the establishment of a French commercial nuclear system resulted from the weakness of the power generation equipment industry. Thus, it was only with the cooperation between CEA and EdF that the industry could participate in the construction of three GCRs similar to Marcoule (38 MW, completed at the end of 1959). Prior to 1968, all plants were of the gas-cooled reactor (GCR) type, with exception of a 10% participation by EdF in the planned SELNI project in Italy. This project was to use the PWR commercial technology from Westinghouse. Framatome entered into licensing agreements with Westinghouse in 1958.¹⁸

While France was developing gas-graphite reactors as a long term strategic option, other technologies were being experimented with, including heavy water-moderated reactors (HWR) and the light water technology, pressurised water reactors (PWR). Following President's de Gaulle death in 1969, the gas-graphite technology was replaced by the LWR, mostly developed under licence agreements with the US duopoly. Akin to the US experience, this development had its origins

17 Uranium supply was guaranteed through Niger and Gabon, at that time still French colonies.

18 Framatome (Societe Franco-American de Construction Economique) was established in 1958 by seven companies of the Empain Schneider Group. Framatome terminated its licence in 1981 and negotiated a new agreement.

in research on nuclear submarine reactors. The establishment of the French civilian nuclear framework was entrusted to two main actors, the CEA and EdF. They served as the executive arm of the Ministry of Industry, which was responsible for energy policy. The CEA was responsible for the entire nuclear fuel cycle as well as research in nuclear physics. Its “Direction des Applications Militaires” (DAM) was responsible for bomb testing at Mouroua. CEA also built the plutonium production plants at Marcoule and La Hague (Schneider 2008).

On the whole, the French civil nuclear programme has largely profited from the military programme and vice-versa; the link with the military has remained strong. For instance, La Hague reprocessing plant was financed in equal shares by the civil and military budgets of the CEA. Schneider (2008: 8) describes this as military cross-subsidisation, which he considers a leading benefactor throughout the entire French nuclear programme.

From national technological options to LWR technologies under licensing agreement

Following the so-called “bandwagon market” of 1966–67 and massive investment in nuclear projects, the US industry compromised the European efforts to develop alternative technologies to LWR and nuclear energy was marketed as “too cheap to be metered” (Cohn 1997).¹⁹ Between 1962 and 1976, the installed nuclear capacity approximately doubled every two years, with a growth rate of over 40% per year. Burness et al. (1990) consider this the fastest sustained growth rate for a US industry in the history of the country.

Because of the technical and commercial success of US LWR technology, European policymakers were torn between resisting the American marketing attack and simply taking up licensing agreements with leading US companies. Economic wisdom led the majority of European companies to strengthen their existing ties with Westinghouse and GE, with the aim of refining their internal capabilities by first gaining access to technical knowledge and then internalising the licence and solving technical problems on their own. Governments similarly made efforts to carve out and direct growth paths using a set of intermediate targets and instruments to foster technological autonomy as a final objective.

Naturally, the relative position of each country with regard to licence assimilation varied and was influenced by economic and political factors. With hindsight, however, one can say that licences brought about advantages when the recipient industries were able to pursue technological improvements on the “product” under

19 In such fixed price contracts, the reactor vendors had responsibility for design, construction and testing of a reactor, including regulatory guidelines.

licence. Given Euratom's failure to promote a European technology, it had become apparent that any nationalistic grounds for a country's autonomous technological path would have been inadequate in the face of the intrinsic fragmentation of the European market and the American oligopoly in the international arena.²⁰

Once the LWR option had become the most widely chosen worldwide, both PWR and BWR (boiling water reactor) technology coexisted in national markets for more than a decade. France was the first country to abandon the BWR technology path and concentrate solely on PWRs in 1975.

6 Determinant factors of success for LWR market penetration²¹

The role of enriched uranium

The availability of enrichment technology and of enriched uranium has often been underestimated as a critical factor contributing to the success of the US technological path. Therefore, here we stress the importance of this element and the way in which pricing policy by the American authorities assisted the US industry's expansion throughout the 1970s and its imposition of LWR technology on the world market.

The availability of enriched uranium can be considered another spill-over from the military activities, and an example of the socialisation of costs as significant as that deriving from the knowledge and experience nurtured under the US AEC and Navy programme applications. The availability of enrichment facilities had a direct influence on the choice of LWR technology. Its impact was immediate, since the employment of enriched uranium permitted some degree of freedom in the alternative nuclear technologies. It also allowed for a certain latitude in the choice of materials and in reactor design, which prevented the "high construction costs and poor material economy" observed in the British case (Burn 1978).

One reason why little interest has been shown in uranium as a leading success factor may be the difficulty of ascertaining the start-up costs of uranium enrichment programmes exclusively for civilian reactor development projects. However, one may reasonably conjecture that whatever the hypothetical cost of such a programme, the expense would have been such that no economic or technical considerations would

20 Commercial strategies and paths differed in the case of experimental reactors and FBR. This field represents an atypical situation, especially for the high degree of European cooperation in R&D and as these projects were carried out independently of the USA.

21 This section draws heavily on Di Nucci (1986).

have justified developing a technology like LWR. On these grounds, countries like Canada, Britain and France, which used different moderators and coolants had no choice for fuel: it had to be natural uranium.

The crucial role played by enriched uranium is underlined by the fact that attempts to privatise the industrial phase of enrichment were unsuccessful, despite early promises by the US AEC that it was prepared to do so, until 1963–64. Moreover, the public monopoly over enriched uranium did not constitute a bottle-neck for the American industry abroad, even with the constraints on the international sale and re-purchasing of uranium. On the contrary, it allowed the industry to transfer costs to the taxpayer for a highly expensive operation. These incentive prices for uranium ore and plutonium were criticised by contemporary observers, but at the same time this move was justified with the need to accelerate the development of a civilian nuclear industry in order to support the uranium production industry (Mullenbach 1963:122).

The US remained the only Western nation where the home industry could benefit from strong military-linked government support. In Europe, the absence of a massive military programme left little hope for the autonomous and parallel development of European technologies. It might be objected that Britain and France also had this support at a later stage uranium enrichment plants, but the Capenhurst and Pierrelatte facilities were designed for military purposes. Their production was modest and insufficiently influenced a change in the preferred technology. While a mix of economic and military considerations (such as the costs of fuel moderators like heavy water and the need for plutonium) had motivated European countries to adopt gas-graphite technology, this proved to be a technical and economic flop. Subsequently, European nations entered into licence agreements with the US LWR vendors.

The search for the optimisation of the whole nuclear system

An additional success factor in the selection of technologies and the industrialisation of military nuclear assets was the active involvement of the US private industry in the fuel cycle. Reactor suppliers could profit from an efficient fuel industry because of their participation in the US AEC promotion programmes; this integration contributed to the optimisation of the system.

Compared to other technologies, nuclear power involved a greater degree of consideration in terms of creating an industry with high organisational and technological standards that were intricately linked to the political and institutional structures. In this respect, the growth of the industry and the progress of LWR technology in the US is an exemplary case of the development of an intimate re-

lationship between industry and the institutional framework, and of the key role that public and private actors played in all aspects of the industry's development.

As a consequence of the many synergies created, the US nuclear system was able to reach a broad turn-key capacity guaranteeing plant construction, fuel rods, and further supplies of uranium as well as reprocessing. Being able to offer such a package from the outset meant that the US industry had a clear comparative advantage for its LWR technology. Our claim is that success did not depend – at least not exclusively – on the characteristics of the reactor offered for sale, but on the system of which the reactor was a part of. The case of Britain clearly shows that the lack of commercial success was mainly due to a nuclear framework which was self-sufficient and closed around its reactor, which ultimately confined national nuclear technology to a single domestic scene.

The British failures demonstrate that a pluralistic approach to technological development in which several alternative strategies are simultaneously pursued may be less costly, in terms of research outcomes, than a monistic approach concentrating on a single project. In the case of the US, the decisive factor in success was not the selection of LWR technology, but the compatibility of that option, of the many explored, with the industrial system that has to accommodate it.

The pragmatic approach by US authorities, what Burn (1978) calls the “selection principle” played an important role. But, unlike Burn, we argue that the choice itself was, in a certain sense, piloted rather than the result of market forces. The choice mechanism is evident from both the Five Year Programme and the various rounds of the Power Demonstration Reactor Programme. On the other hand, the best experimental results were obtained with prototypes that were later abandoned. In fact, the Joint Committee on Atomic Energy concluded in 1954 that of the five different reactor technologies developed for civilian use, the PWR appeared to be the least promising due to its conservative design (Cowan 1990). How then, was it able to emerge as the dominant technology? To address this question, the first thing to consider is that the LWRs, though less advanced than other technologies, were chosen for their commercial viability. Unlike other technologies, they presented fewer obstacles to being scaled up from the prototype stage. LWR was thus the only design ready for full-scale construction. Moreover, its deployment was necessary as a demonstration of the potentials of commercial nuclear power and to promote the “Atoms for Peace” Programme. With Cowan (1990: 566), we maintain that the first-comer technology which can advance along its learning curve will dominate the market.

This, of course, is not the whole story. An additional and more fundamental explanation is that unlike many national nuclear programmes, where the failure to export reactors was largely due to the inability to internationalise their productive

structure, the US' technology was the only one to offer continuity and a greater flexibility. Any strategy can be adopted for the commercialisation of a product, but when an entire technological system is to be exported, the strategy which pays off is that which best fits what has been named the principle of technological-industrial continuity (Di Nucci and Pearce 1989). Solutions and systems that are too far from current technological frontiers are unlikely to succeed, since they would require the greatest amount of technical and industrial adjustment and transformation. The strength of the US nuclear system was its ability to be exported as a reactor-and-service- package, satisfying the technological-industrial continuity criterion.

The pull of the market

The success factors outlined thus far would have been of little avail if steps had not been taken to turn potential demand into orders. Such policies in the US and Europe differed not only in their manner of creating internal demand, but also in the paths pursued to reach this target. European strategies, at least initially, were inspired less by export and commercial criteria than by the urge for technological and energy autonomy. In contrast, the US AEC tried to stimulate demand from electric utilities by offering advantageous conditions and incentives, such as subsidies and a pricing policy for enriched uranium. With this approach, the size of the US domestic and export market were directly influenced by government policy until the mid-1960s.

A major turning point occurred in 1964, at the time of the third Geneva Conference. GE had established itself domestically and internationally as a reactor vendor. The company had moved quickly in improving the original design and scale-up of prototypes and offered turnkey contracts for large scale reactors at fixed prices. Thirteen reactors were ordered on a turnkey basis by electric utilities (Burness et al. 1980). Thus, when GE published its price list for BWRs in 1964, the price quoted for the Oyster Creek plant had already set new cost targets that neither national nor European competitors could ignore. This enabled the company to present themselves as having the most feasible and economic design (Cohn 1997).

GE's price list had an enormous impact. It represented a nuclear power plant as an "autonomous" commercial good and placed potential clients in a position to refer to a definite product with a definite price, much lower than those of its competitor, Westinghouse. Of course, the venture resulted in corporate losses; however, it also indicated that GE was not only likely to reap the benefits of cost socialisation of the early development phases, but that it was also prepared to take risks in commercial ventures.

Another important success factor is that in 1964, an amendment of the Atomic Energy Act granted the US AEC permission to lease nuclear fuel directly to market

actors. The timing of the GE price campaign coincided with the readiness of the US utilities to begin adjusting to previous under-capacity. The combination of demand and of the low, seemingly competitive prices for power generation, plus the kind of contracts for which the vendor guaranteed a fixed turnkey supply, triggered a boom in US plant orders. Seven units were ordered in 1965 and eight in the first half of 1966, to be followed by 13 in the second half of 1966 and 31 in 1967 (Burness et al. 1980:190). Though turnkey projects were costly investments for vendors, the completion of the turnkey units stimulated demand for new reactors and subsequent sales. The time period which followed was characterised by a tremendous flow of new orders, so much so that this era has been referred to as the 'Great Bandwagon Market.' Whereas 78 reactors had been ordered over the 12-year period between 1955 and 1967, 166 reactors were ordered for projects across the USA between 1968 and 1973, with 38 units ordered in 1972 alone (Bernd and Aldrich 2015).

A key observation is that in the decade 1963–1973, the US domestic demand alone offset the aggregate demand of the world market. The size of the internal market enabled the industry to pass the minimal threshold in physical and investment terms necessary for an autonomous take off, and to speculate on the promise of possible economies of scale including learning effects, which was hoped to trigger success on the export market. Two aspects of this cumulative effect are illustrated by the widespread network of licence agreements that US companies started in Europe and Japan. The third Geneva Conference therefore marked the establishment of the US commercial and technological supremacy. It simultaneously dealt a blow to the commercial aspirations of many autonomous national nuclear technologies in Europe. Licences became the major vehicle in US export policy.

The scale of the reactors increased dramatically and most of the plants within the 'Great Bandwagon Market' were considerably larger than older reactors (400MWe or greater). By the end of 1970, the entire nuclear industry had only accumulated 11 years of operating experience on units of this size. As the demand for electricity in the US decreased dramatically in 1973, the first signs of the industry's problems emerged. Most reactors faced construction delays and massive cost overruns; orders for nuclear power plants started being cancelled, with 12 projects called off before the end of 1973 (Bernd and Aldrich 2015). In 1975, only four reactors had been ordered, and just nine more were ordered in the three years that followed. The last order for a new nuclear power plant came in 1978. A year later, in 1979, the Three Mile Island's accident occurred and the collapse of industry began.

7 Conclusions

Our analysis has pointed out exogenous and endogenous factors affecting the long-term development and diffusion of the LWR technology: the military spill-over effect; the use of enriched uranium and its restrictions; the subsidised price of enriched uranium; the choice of a commercial reactor based on the industry's capacity to accommodate the technology and internationalise the whole system; and, last but not least, the scale of the nuclear programmes. The causal interactions at work here were unidirectional, but their influences have been mutual. New nuclear technology was not simply tested and then integrated within a system; its development was embedded in interactions with this system. Although there are similarities between national experiences, very distinct national stories have emerged.

The US: The first-comer in enhancing the leading LWR technology was an innovator that benefited from early government infrastructure and support to commercialise the technology and benefited from military spill-over effects.

The UK: An example of the failure of a nuclear system based on a domestic autonomous technological pathway. The centralised framework and the idea that technical progress could occur despite negative signals from the international market, combined with institutional inertia, had a strong adverse effect on the industry. Ultimately, it could not rely on any suitable instruments to compensate for an international market that opted for LWRs.

France: A latecomer in the development of LWR technology. Its experience indicates the timeliness of giving up a national technology without a commercial future and taking on the risk of starting practically from scratch under licence. The extremely integrated decision-making framework, the nurturing attitude of the French government and the national electric utility bestowed a steadily growing market and learning economies.

The initial nuclear development in these leading countries was characterised by a plurality of base technologies, following the experience gained through strategic and military activities. National differences in these experiences led to correspondingly different national civilian frameworks and technological choices. In the initial development phase, the US enjoyed a virtual monopoly on uranium enrichment, backed by military financial support. It could opt for LWR technology accordingly.

The availability of enriched uranium is arguably the most crucial factor in the US' comparative technological success and market advantage. This can therefore be regarded as the cornerstone of the US export policy and success. In contrast, the absence of enrichment facilities in Europe, along with the need for plutonium for military purposes, guided France and the UK to pursue gas-graphite and Canada to select heavy water as a moderator.

Although the US was not alone in early nuclear development, its emphatic leadership came about through a series of crucial factors. The US AEC's financing of almost all nuclear R&D, along with its direct role in funding and subsidising the majority of the early plants, proved to have a decisive and positive influence on the industry's development. Domestic contracts became a key vehicle for eventual export sales, even though government regulations and administrative controls initially limited the scope of power plant export. The marketing of nuclear reactors occurred within a framework determined by international organisations, treaties, bilateral agreements and national laws, and was also influenced by economic and political relations with the recipient countries. The transfer of nuclear technology, mainly to Europe and Japan, was assisted by a certain liberality on the part of the licensors, but also by restricting expertise on the nuclear fuel cycle for military purposes. In this process, Britain was to suffer most and France was also adversely affected. Both countries eventually opted for LWR technology in 1979 in the former case, and a decade earlier, in 1969, in the latter.

The inherent characteristics of the nuclear plant as a saleable good, and the resulting implications for its development required a special role that only national governments could fill. At the same time, the industry needed specific government support, whether for selling abroad (as in the case of GE and Westinghouse), or for its engagement in the manufacturing of components imported from technology leaders (in the case of Europe). Either way, backing and promotion by governments was essential for various reasons, military development and spill-over and the nationalist incentive that made the industry desirable even before economic competitiveness had been achieved.

We have tried to separate the progressive attack by the US oligopoly on the national and international market into distinct temporal phases. The marketing of the US power plants followed two strategies: one amounting to the sale and later export of the nuclear reactor as a product; the other as the export of the entire nuclear productive structure. The former strategy applies to the period 1963–72, and in particular between 1962 and mid-1966. During this period, GE and Westinghouse sold turnkey plants to US public utilities and the contracts were available under fixed price terms (Burness et al. 1980; Bernd and Aldrich 2015).

GE ended its turnkey contracts sale offensive to US electric utilities in June 1966. According to Burness et al. (1980), GE and Westinghouse took combined losses on the contracts upwards of \$1 billion. However, the financial losses they suffered during the turnkey era can be considered an investment “in obtaining information through “learning by doing” in an effort to capture rents from the second generation of reactors” (Burness et al. 1990: 189). Finally, the US companies ceased offering turnkey contracts because of the cost risks.

The second stage occurred through the transfer of knowledge via the sale of patent rights and licences, without direct industrial investment abroad, and by establishing subsidiaries and internationalising industrial capital via direct investment of risk capital in a foreign country.

As we have explored in this chapter, there are good grounds for claiming that the early commercial success of LWR and the establishment of the US oligopoly (first domestically and then in the global market) is a rich example of the combined effects of a technology push (via the US AEC activities and military spill-over effects), market pull (bandwagon market) and market push (via competition among utilities to improve technical standards through innovation). A civilian nuclear industry was created in part to legitimatise the continued development of atomic weaponry. In the haste to develop nuclear power plants, economic and technical considerations were often secondary. A military model was selected for civilian use because it initially provided a dual purpose fissile material production capacity, rather than simply because it was immediately available (Bupp and Derian 1978).

Alleging the importance of a production system which is common all over the world, Cowan (1990: 552) claims that “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”. In the US, the choice of technology to be pursued in commercialisation encouraged autonomous technological advances for the options which could be developed while maintaining a certain continuity with the pre-existing industrial structure (Di Nucci 1986). Other, more “innovative” paths were to stay at the experimental level and be undertaken under governmental support, not directly by the industry – and they have remained “experimental” until today.

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