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ADVANCED TECHNOLOGY AND PUBLIC POLICY: DEVELOPMENT OF THE NUCLEAR POWER REACTOR IN SIX NATIONS

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ADVANCED TECHNOLOGY AND PUBLIC POLICY:
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by

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I. INTRODUCTION

The appropriate role of the government in promoting the development and commercialization of advanced technologies has been and continues to be a matter of considerable debate on the normative (Mansfield, 1968), strategic (Eads and Nelson, 1971), and the tactical (Baer, et al., 1977) levels. That is, ought the government to intervene in the market to promote a new technology; if so, what sort of general guidelines or criteria should it employ; and what specific tactics are thought to be the most efficacious? These questions, however pivotal, generally overlook the organizational issues that determine the institutional actors in the development, the roles they play, and how they came to play them. To understand how public policy influences technology, we need to ask what sort of political, social, and economic forces motivate, shape, and direct the research, development, demonstration (RD&D), and diffusion of advanced technologies and how do science and technology heuristically act to reshape or affect these forces? While these issues have been treated sui generis in a few case studies (see Logsdon, 1970, for one example), they have not been analytically treated across a number of comparable case studies such that policy generalizations can be formulated and extracted. Such is the purpose of this paper.

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The nuclear power reactor is an excellent set of directly comparable examples of government involvement in the development and diffusion of a single advanced technology. Although the American atomic power reactor dominates the world reactor market and is by far the most thoroughly documented (see Perry *et al.*, 1977), at least five other national governments and industries actively worked to develope their own indigenous nuclear reactor technology and industry. The similarities and differences in the respective development and dissemination programs of the United States, the Soviet Union, the United Kingdom, the Federal Republic of Germany, Canada, and France can serve as a limited arena for posing and testing policy issues regarding the institutional factors shaping the important interactions of technology and public policy. The necessary caveats on excessive extrapolation from a restricted data base, especially one that deals with distinctly different political and cultural entities (Cyr and deLeon, 1975), must be observed. Still, these reservations should not be permitted to obscure the individual narrative threads which, when treated collectively, weave a coherent tapestry depicting the organizational roles of the various actors that make high technology a matter of public policy.

Some important qualifications are in order. We deal here with only high cost, advanced technologies which are destined for the civilian sector. This precludes the development of technologies whose nominal costs do not require government support or whose development is for military purposes, an area which is the exclusive developmental domain of the government (either directly or by contract). Following Allison (1971), the analyses are couched in terms of the institutions which conducted the development and diffusion rather than in terms of national actors (i.e., "the U.S. chose to build a breeder reactor") or individual persons, for, as Mejone (1977: 175) notes, "In assessing technology, we are really evaluating institutions." Finally, the cases compared here are restricted to the RD&D and subsequent diffusion of "slow" nuclear fission reactors whose primary function is the generation of electricity. This implicitly includes research reactors developed as part of the power reactors RD&D process and excludes the numerous RD&D programs for "fast" fission reactors, fusion reactors, and nuclear weapons programs. Obviously, the development of nuclear energy sources cannot be viewed in pristine isolation from other nuclear research projects; the American commercial light water reactor was largely an outgrowth of the U.S. Navy's nuclear submarine propulsion program. Still, other nuclear research programs will be referenced only as they concern the development and diffusion of the atomic power reactor.

In addition to the introduction, this essay is organized into three parts. Section II will present an analytic framework for viewing the critical organizational factors hypothesized to affect the interactions between technology and public policy. Section III will examine these in light of the development and dissemination of nuclear power reactors in six nations. Finally, Section IV will offer some tentative policy observations and note that the developmental travails experienced during the nuclear reactor RD&D are not restricted to this one specific class of development, that, in fact, the institutional patterns observed here are found in other advanced civilian technology programs, such as the supersonic transport, rapid transit systems, and communication satellites. In brief, then, the analytic framework can be treated as a basis for a more generic understanding of institutions and technology development in the public sector.

II. MULTIPLE ACTORS, MULTIPLE OBJECTIVES, DIFFERENT TIMES

Previous works on national technology development programs have been somewhat restricted in their scope and have therefore been able to define a discrete and singular criterion for assessing the "success" or "failure" of a given development or demonstration program. This is true for both national and international developments, for both individual and comparative case studies. Baer, Johnson, and Merrow (1977) suggest in their case studies of federally-funded demonstration programs that the simple resolution of cost and technical uncertainties was the only criterion the government wished to consider when evaluating its RD&D programs. Costello and Hughes (1976) compare the British/French development of the supersonic transport (SST) with the analogous American and Soviet SST developments with the implicit national objective being the production of the first SST to fly passengers on a regularly scheduled route. Joskow (1977) argues that the measure for a national nuclear reactor RD&D program is the nation's ability to produce indigenously a viable reactor system. Burn (1967) employs the identical objective function to buttress his attack on the British nuclear reactor development program.

However convenient or common the singular evaluation criterion assumption is, it is misleadingly simplistic and may be fundamentally false when dealing with the comparative analysis of large, complex programs. As Verba (1976: 117) writes, "The patterns for which we try to account in comparative politics . . . are immensely complicated and cannot be accounted for by one or two simple causes. Only by considering the combination of a large number of factors can we hope to begin to account for the relevant variations." The adherence to a simple evaluation metric can flaw both the research paradigm and, perhaps even more important, whatever policy recommendations that emerge from the research. Drawing upon the work of organizational theorists (e.g., March and Simon, 1958, and Cyert and March, 1963), Neustadt (1970) and Allison (1971) have argued persuasively that large collectivities such as governments are nothing more than aggregations of different, often divergent groups. These component groups have and their actions reflect competing objectives, even (or especially) when they are "cooperating" towards apparently congruent goals (Mohr, 1973, discusses organizational goals). Allison's examination of the Cuban missile crisis as a study in "bureaucratic politics" is still the best example of how groups within a government can work at cross or even counter purposes; Morison (1966) demonstrates how the observations gleaned from diplomatic history are equally applicable to technology innovation, development, and adoption.

Drawing upon this literature, we can compare the national developments of nuclear power reactors in six nations using the following explicit assumptions regarding the "success" or "failure" of each program. First, there were a number of major institutional actors in each developmental drama, each vying for center stage and each, at different times during the development and diffusion, having greater or lesser roles to play. Second, because there were multiple actors and each had its own peculiar organizational goals, there were multiple objectives that were simultaneously being pursued, which may or may not have been harmonious with one another. It follows, then, that the intensity with which a national program was perceived to have been motivated by a particular objective at any given moment was largely a function of which organization (and its allies) was preeminent at that phase of the developmental process. Third, and finally, technology developments of the magnitude considered here can be characterized as affected by a number of "attributes" of the national development system that were influential (by either their presence or absence) in determining the progress of technology developments.

Based upon these assumptions, we can pose an analytic framework which permits us to examine multiple cases of technology developments from a comparative perspective. The proposed analytic framework for technology development and dissemination is predicated on a series of interactions between a set of institutional <u>objectives</u>, which represent various political and economic goals underlying the technology developments, and a set of <u>attributes</u>, which define and characterize these same developments.* The relative importance of the posited objectives and attributes should change during the course of the development with the vicissitudes of the prevailing political, social, and economic conditions. The sets or vectors of objectives and attributes are listed in Table 1:

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*At this stage of theory formulation, the key consideration for these sets of objectives and attributes should not be their exactitude in structuring a rigorous, predictive framework. More appropriate criteria for the proposed lists are their utility, inclusiveness, and internal consistency as they are defined rather than their premature (and perhaps debilitating) precision.

Objectives of Technology Developments

Science for Science's Sake
National Prestige
Development of Efficient Technology
Political Equity

Attributes of Technology Development

Active Scientific Community
Integrated Technology Delivery System
Concomitant Military Program
Early Starter
National R&D Heritage
Multiple Technology Options
Resources Invested

Table 1: Objectives and Attributes of Technology Developments

Let us briefly define what each of these represent.*

Objectives

Science for Science's Sake is defined as government support of basic scientific research in which the principal consumer is scientific knowledge and practical application is an innocent bystander. The objective of Science for Science's Sake addresses the amorphous goals of scientific advancement and, more distinctly, directly satisfies the research interests of a limited number of research personnel within the scientific communities and their sympathizers within the government (see Price, 1965). Project MOHOLE and nuclear accelerators are two noted examples (see Greenberg, 1967, and Lambright, 1976). As Caty (1974: 167) reported to the OECD, "fundamental research became simply one national objective among others" during the 1960's.

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*For more detailed explanations of the objectives and attributes, see deLeon, 1978: Chapter 2.

National Prestige is one reason for committing a nation's resources to the development of a technology. Logsdon contends that President Kennedy's main reason for declaring that an American would land on the moon within a decade regardless of the expense was his desire to harvest the immense international prestige that would be accorded the first nation landing a man on the moon. Kennedy explained that, "If you had a scientific spectacular on this earth that would be more useful--say desalting the ocean--or something just as dramatic and convincing as space, we would do that." (Quoted in Logsdon, 1970: 110-111). Similar sentiments can be found underlying the respective British and American decisions to build a SST and the nuclear ship "Savannah."

The objective of the Development of an Efficient Technology is to deliver a new technology capable of competing on a price basis with the other alternatives available for meeting a specific demand. In other words, can a nation's scientific and technical communities produce, say a personal rapid transit system capable of competing with the private automobile or municipal bus lines? Although government subsidies might cloud a clean interpretation of economic viability, market approximations are usually available. A second objective for the development of an efficient technology would be for export purposes, thus benefiting certain sectors of a nation's industry and, simultaneously, the national balance of payments. The French and the British governments clearly viewed the Concorde as a technology principally built for export. For a nation whose trade balance appeared precarious, such as Britain's after the Second World War, the development of an efficient, competitive technology for export purposes could be viewed as a particularly attractive investment and a worthwhile policy objective.

The Political Equity objective represents the political process of resource allocation or reallocation within an economy as determined by the interplay of political interest groups (Truman, 1951). The resulting distribution reflects both the political resources of different interest groups and the government's response to them.

Attributes

The Active Scientific Community attribute is meant to capture the role of a nation's scientific community or its patrons in promoting a government's involvement in and financial support of large-scale scientific research. It implies an attempt at establishing priorities and procedures during the formative RD&D periods (for multiple illustrations, see Greenberg, 1967, and Lambright, 1977).

The Integrated Technology Delivery System (TDS) attribute describes the degree of cooperation or coordination among the major institutional actors in the development and dissemination of a technology. Originally described in general terms of a developer, a vendor, and a consumer by Wenk and Ezra (both 1975), the key here is the extent of "integration" exhibited by a nation's TDS or, more exactly, the degree to which the three organizational actors (or set of actors) are able to coordinate their roles within and among the phases of the development and diffusion and the way in which the roles complement or conflict with each other. An integrated TDS suggests three distinct institutional roles (although overlaps can and do occur), within which the actors have some degree of latitude. It also implies that no one actor or organization dominates the others throughout the development, demonstration, and dissemination periods.

The Concomitant Military Program attribute inquires whether a nation's civilian technology development programs are carried on in conjunction with a military program whose research could positively benefit the civilian program. For example, did military research on the supersonic manned bomber have a beneficial "spill over" effect on the SST?

The Early Starter attribute indicates if a technology development is in the technological vanguard of specific technology development programs relative to other national efforts or is it an example of "buying in" at a later date when the technology has largely been developed elsewhere. Gilpin (1970) has argued that this choice might be a deliberate decision in a nation's R&D strategy and, as such, has a significant effect on the programmatic objectives.

The R&D Heritage variable is meant to capture a nation's "track record" of past performance in large scientific or R&D projects. In other words, is there a national history of technology developments and innovation diffusions? It also implies the presence or absence of the institutions and personnel making up that tradition. Caty's (1974) review of the patterns of basic research in the OECD nations is but one of many illustrations.

The Multiple Technology Options attribute is based on the literature on military weapons systems R&D which holds that successful development projects requiring major technological advances are characterized by multiple and competitive research options (see Glennan, 1967, and Scherer, 1964). Specifically, this attribute asks whether there were multiple technology options maintained sufficiently late in a technology development for the relevant policymakers or technology consumers to have a choice among alternatives.

Finally, the Resources Invested attribute refers to the financial and human resources, both government and nongovernment, expended on a given technology development; this includes government subsidies and income forgone due to tax entitlements. This variable reflects the large amounts of money spent over extended periods of time to develop given technologies which are important for two reasons. First, and most obvious, adequate resources must be invested in a technology so that it might be developed to fruition. Second, but no less important, the prior research invested can have a significant effect on pending and future funding decisions, an investment calculus which contradicts the microeconomic theory of the firm and its tenet of marginal costings (see Wolf, 1970). There are powerful organizational and political reasons why a government (or any sponsor) would deliberately reject marginal cost analysis and choose to honor sunk costs with continued funding, such as a fear of increased unemployment, the loss of a critical industrial sector, or a general unwillingness to admit to a program's failure as signaled by a termination of its support. The actual influence of sunk costs thus represents the political baggage that previous investments in a technology bring to present decisions rather than "rational" economic decisionmaking.

The Developmental Periods

A changing set of political, economic, and technological conditions may be expected during the course of a technology development. This dynamic suggests different stages in a development which, in turn, present different problems. For our purposes, we can identify three stages: the development stage; the demonstration stage; and the diffusion stage. Assuming that different conditions prevail within these stages, one can hypothesize a changing hierarchy of the participating institutions and their objectives as reflected in altered emphases on the different objectives and attributes (Lambright and Teich, 1976). The transitions between the periods are especially critical because they suggest how readily the development can move to new and more appropriate objectives or is bound to outmoded ones. The explicit recognition of distinct periods also inserts an element of developmental and institutional dynamics into the analytic framework.

Relationship of Attributes to Objectives Over Time

In the proposed analytic structure, the multiple objectives and the institutions that pursue them as organizational goals are juxtaposed to define the national developmental programs. The objectives are defined by the national developmental attributes. The presence of specific attributes is reflected in the relative importance of particular objectives in the overall national development program at a given time. This functional relationship can conveniently be displayed (see Figure 1) in a matrix format which suggests the possible interactions between objectives and attributes. The objectives columns are largely couched in terms of organizational goals while the attribute rows are cast in terms of technology development variables. As such, Figure 1 graphically depicts the issues of what economic, political, and institutional forces shape government-sponsored RD&D programs and, conversely, what effect scientific research and technology development programs have upon a nation's RD&D policies.

Objectives of Technology Development \ Attributes of Technology Development	Active Scientific Community	Integrated Tech. Del. System	Concomitant Military Program	Early Starter	National R&D Hertige	Multiple Tech. Options	Resources Invested
Science for Science's Sake							
National Prestige							
Development of Efficient Technology							
Political Equity							

Figure 1. Framework for Technology Development: Objectives/Attributes Matrix

Let us now turn to the comparative analysis of the nuclear reactor research programs in the United States, Canada, Britain, France, West Germany, and the Soviet Union to test these relationships in the context of the analytic framework.

III. THE COMPARATIVE ANALYSIS OF NATIONAL REACTOR DEVELOPMENTS

Before placing the prism of the analytic framework against the multiple national reactor development programs, it is necessary to review the programs to acquaint the reader with the major events and institutional actors which defined the respective developments. (More extensive reviews of the national programs and detailed references are in deLeon, 1978.)

The National Programs

The United States power reactor program was a direct out-growth of the wartime program which developed the atomic bomb. Immediately after the war, American nuclear scientists began pressing for relaxed security conditions and the application of atomic energy to peacetime uses. Congress, in 1946, passed the Atomic Energy Act which severely restricted the foreign dissemination of U.S. nuclear research and created the Atomic Energy Commission (AEC) and its congressional counterpart, the Joint Committee on Atomic Energy (JCAE). During the late 1940s and early 1950s, Westinghouse and General Electric (GE) contracted with the AEC for research on atomic reactors. In 1953, the AEC initiated a series of incentives for utilities and private industries to demonstrate a variety of different reactor technologies including a breeder, a boiling water reactor (BWR), and a pressurized water reactor (PWR).

In 1954, the AEC, Westinghouse, and Duquesne Light Company agreed on the construction of a 60 MWe PWR at Shippingport, Pennsylvania, which was completed in late 1957. The Yankee power station, a 140 MWe PWR, was built by Westinghouse in Rowe, Massachusetts, under the AEC incentive program; Indian Point (a Westinghouse 151 MWe PWR built for Consolidated Edison) and Dresden (a GE 180 MWe BWR built for Commonwealth Edison) were contracted for in the mid-1950s and completed in 1960.

The AEC and JCAE were still dissatisfied with the lack of enthusiasm on the part of the utilities and industry so a new set of demonstration reactor incentives were announced. The JCAE amended the Atomic Energy Act in 1954 with the clear "expectation that private industry would begin to invest in nuclear R&D power plant construction, thereby reducing the role the federal government might have to play." (Allen, 1978: 37) In 1957 Congress removed another impediment by passing legislation limiting the utility's liability in case of nuclear accident. Still, with the exception of the GE BWR at Haddam, Connecticut, in late 1962, there were no orders for commercial-sized reactors in the United States for five years.

In late 1963, New Jersey Central Power ordered its Oyster Creek facility, a 515 MWe BWR, from GE at what was considered a breakthrough price; Niagara Mohawk placed a similar order with GE for its Nine Mile Point power station at the same time. GE and Westinghouse both began to offer utilities fixed price, "turnkey" contracts; i.e., they contracted to build the plant for a specified price and turn it over to the utility in operating condition. By the end of 1965, this offer was seen as precipitating the long-awaited nuclear breakthrough in the United States. In 1965, three GE BWRs and three Westinghouse PWRs, averaging nearly 700 MWe apiece, were ordered; in 1966, 20 LWRs were ordered and in 1967 another 30 orders (averaging over 850 MWe each) were placed. As Hogerton (1968: 21) commented, "Nuclear power, like the boy next door, seems to have grown up overnight. That it has indeed come of age is incontrovertible."

The Soviet Union power reactor program also emerged from a wartime nuclear research program. Spurred by the propaganda potential, the Soviets built the world's first electricity-generating atomic reactor, a 5 MWe light water cooled and graphite moderated reactor at Obninsk, just prior to the 1954 Geneva Conference on the Peaceful Uses of Atomic Energy.

Soviet atomic scientists and technicians, working in a number of nuclear research centers, developed at least six different reactor technologies and chose to demonstrate four reactor types--the light water cooled, graphite moderated reactor (LWGR); a PWR; a BWR; and a graphite, boiling water reactor--before standardizing on the first two. The evidence underlying these choices is sketchy. The primary advantages of the LWGR were its similarity to the early Soviet plutonium-producing reactors, the relative ease of construction, and the putative greater safety of reactor operations. The PWR apparently offered some construction savings and greater operating efficiencies (see Pryde and Pryde, 1974: 27). There is no indication why the BWR option was discontinued except for the possibility that Soviet heavy industry was reluctant to construct three types of reactors (Petrosyants, 1975: 198).

Soviet reactor RD&D was relatively straight-forward although Petrosyants (1975: 113) does allude to "unavoidable troubles and excitement . . . caused by phenomena which were not immediately explained" during the initial operations of the Novovoronezh-1 PWR in the mid-1960s and the reticence of heavy industry to support Soviet reactor RD&D (Petrosyants, 1976: 18-19). Wilczynski (1974: 570) reports that the early costs of "nuclear power appeared to be prohibitive . . . and that nuclear power could not become competitive before 1980" but Soviet authorities have explicitly stated that costs of operation were not relevant during the demonstration phases of reactor development (Petrosyants, 1975: 115) even though they were closely monitored.

Following a series of LWGR and PWR demonstration reactors, Soviet officials decided to begin full-scale dissemination of nuclear power reactors (Shabad, 1977, and Pryde and Pryde, 1974: 26), planning a series of 1000 MWe reactors mostly scheduled for completion in the 1980s. They are to be built in the western portions of the Soviet Union because almost all of its fossil fuels are situated in the eastern provinces of the nation, thus saving Soviet utilities the expense of transporting petroleum or coal across the immense Russian land mass (see Emelyanov, 1971: 41, and Petrosyants, 1976: 19).

Like the Soviet and American development programs, the Canadian power reactor program had its genesis in the wartime efforts to develop atomic weapons, when Canadian researchers were assigned the responsibility to investigate the potentials of deuterium oxide or "heavy water" (see Eggleston, 1965). After the war, Canadian nuclear researchers continued in this vein, partially because of their prior research and partially because they were excluded from participating in U.S. nuclear research by the McMahon Act. In September, 1945, the Canadian Zero Energy Experimental Pile went critical, thus making it the world's first nuclear reactor outside the United States. Canada--alone of the wartime allies--chose not to pursue the concurrent development of nuclear weapons.

In 1946, the Canadian government passed the Canadian Atomic Energy Act which formed the Atomic Energy Control Board, basically the Canadian regulatory body. In 1952, Atomic Energy of Canada, Ltd. (AECL) was created to be the operational agency for developing nuclear energy.

In 1953, AECL officials began to plan for a nuclear power demonstration (NPD) station at Rolphton on the Ottawa River, about 30 miles downstream from the AECL's main research facility. The AECL was to design the plant; Ontario Hydro would provide the site, personnel to operate the facility, and the conventional portions of the plant; and Canadian General Electric would design and manufacture the components. Financial responsibility was divided 70%, 25%, and 5%, respectively. AECL engineers made a number of major design modifications for the NPD that have characterized the Canadian Deuterium Uranium, or CANDU, reactor ever since. First, as the name implies, the reactor was both cooled and moderated by heavy water. Second, it would operate on natural (i.e., unenriched) uranium because the Canadians had been denied enriched uranium by the U.S. McMahon Act and, in any case, had ample indigenous supplies natural uranium. Fuel was to be placed in the reactor in individual tubes with pressured heavy water circulating within each tube; there was to be no single large pressure vessel (see McIntyre, 1975: 22). The NPD went critical in March 1962, and in June began feeding 22 MWe into the Ontario Hydro transmission lines.

In 1959, even before the NPD was completed and while experiencing great difficulty in manufacturing sufficient heavy water to operate its facilities, the AECL and Ontario Hydro announced plans to build a full-scale CANDU reactor at Douglas Point, Ontario. In 1964, Ontario Hydro ordered two additional CANDU reactors, rated at 500 MWe each, and contributed 40% of the costs, the central and Ontario governments paying the remainder. At approximately the same time, Hydro Quebec ordered a 250 MWe plant and Canada sold two CANDU reactors abroad. By the early 1970s, then, Canada utilities had made a major commitment to the CANDU reactor. The president of the AECL was able to state with some justification that "On a per capita basis, Canada leads the world in nuclear power generating. For December 1973, this was some 45% more than in Britain, 85% more than in the U.S." (Gray, 1974: 476).

The development of the nuclear reactor in the Federal Republic of Germany was markedly different from any other nation's reactor RD&D program in at least three ways. First, it was not begun until ten years after the other nations surveyed because of the terms ending World War II and the ensuing Cold War. Second, the West German program, when initiated, was based almost entirely on exogenous technology and materials, including enriched uranium supplied through the U.S. Atoms for Peace Plan. German technicians were able to choose among demonstrated technologies. And third, the R&D was pioneered and spurred by utilities and private industry; the federal government was a reluctant actor until well into the German reactor development program. As Nau (1974: 73) points out, "domestic and foreign policy considerations in Germany called for a cautious and fragmented approach to nuclear policies."

In 1955, the Federal Republic rejoined the European community of nations. On the urging of electric and chemical companies, the federal government established in 1956 the Ministry for Atomic Questions which was given the primary responsibility for merely coordinating German nuclear R&D policies and priorities among federal, state, and private organizations. A government advisory committee of scientists, officials, and industrialists was also created in 1956. The federal atomic research budget was only $11 million. As <u>Nuclear Engineering</u> ("Germany," 1960: 543) observed, "Of all the major industrial countries with atomic commitments, development work in Germany is probably the least well organized."

In 1957, the government advisory committee issued an unofficial five-year development plan, the Eltsville program, which called for the construction of five different demonstration reactors and "manifested a clear concern for the national integrity and competitive place of German programs" (Nau, 1974: 86). Not surprisingly, the reactors were to be built by consortia of industrial firms and utilities with little federal monies involved. The choices of reactor technologies ranged from the American LWR to the more European high temperature gas reactors. The German national strategy was clear: to depend on the short run on largely proven reactor technologies while developing an indigenous set of technologies and capabilities.

In 1958, a Bavarian utility contracted with a German industrial firm to build a 15 MWe prototype BWR, which became operational in 1960. This facility was built without any federal funding, but it was soon clear to all concerned parties that significant amounts of federal funding were required if the German nuclear research community and industry were to be competitive with the French, English, and American reactor programs. The rest of the Eltsville prototype reactors benefitted from heavy federal government subsidy; for example, the German HWR prototype was financed over 80% by the central and state governments.

Even so, the federal government was careful not to give the appearance of being too directly supportive of full-size demonstration nuclear reactors, as opposed to prototype reactors. The first commercial-sized nuclear reactor in Germany was the Gundremmingen 250 MWe BWR, which was financed by two German utilities, built under a GE license, and fueled with enriched uranium provided by the United States through EURATOM. The reactor selection, made in 1961, was between the American-designed BWR and a British gas-graphite model. The choice was particularly critical for German and other European nuclear reactor firms, for it clearly signaled the German preference for American over European reactor technology and enriched uranium over natural uranium fuel. The twin choices were reaffirmed in 1964 when a 268 MWe BWR and a 345 MWe PWR, both built under American licenses, were ordered by German utilities.

In 1967, after losing a reactor contract to a French company, the two major West German reactor construction firms, with the clear support and urging of the government decided to consolidate their reactor branches. In 1969, Siemens and AEG announced the formation of a joint nuclear engineering subsidiary. Both firms allowed their licenses with Westinghouse and GE, respectively, to lapse in the early 1970s.

Thus, by as early as 1965, the editors of Nuclear Engineering ("Germany," 1965: 317) could assent:

> Say no more of Germany's late start, for this has been caught up. The comprehensive programme which many thought too broad and ambitious to be accomplished with the time and effort available is being achieved rather than cut back. And Germany has shown faith in the practical future of nuclear energy by placing more power station orders during the past year than any other country.

The British program for developing nuclear power reactors closely parallels the Canadian and American programs, their wartime development allies. Like the American program, British nuclear researchers were largely influenced by the military requirements of nuclear research; plutonium, more efficient than uranium for atomic bombs, became the key to their nuclear development programs, thus effectively eliminating the LWR, with its fuel requirement of enriched uranium, as a technology option. Like the Canadian program, the British were excluded from U.S. nuclear research by the McMahon Act, thereby further precluding the enriched uranium options. However, the destruction of the wartime English economy and fears of a fuel shortage motivated the British atomic establishment to move forcefully into nuclear power research, an enthusiasm shared by the Labour government.

In 1946, the government's Atomic Energy Act organized the British nuclear research program within the Ministry of Supply, England's defense procurement agency. The changed emphasis from nuclear weapons to power reactors was marked in 1953 by the establishment of the United Kingdom Atomic Energy Authority (AEA), which assumed all responsibilities for nuclear research. Unlike the developments reviewed above, the AEA research program effectively treated the electrical construction industry as suppliers; little atomic research was conducted by British industry. Another critical difference is that the AEA had only one customer, the Central Electricity Generating Board (CEGB), the nationalized electric industry supplying power for almost all the United Kingdom.

In 1953, the AEA approved plans for the world's first large nuclear power reactor, the 138 MWe graphite moderated, gas cooled, unenriched uranium Calder Hall facility. In October 1956, the plant was officially inaugurated and delivered the world's first nuclear-generated electricity into the CEGB's grid, an event heralded as that "day the United Kingdom atomic energy program, which had been through a good deal of depressing weather, broke through into the sunshine of international prominence" (Hinton, 1958: 29), and staked the British claim for leadership in nuclear power reactors.

In February 1955, the government issued a White Paper calling for the construction of 12 gas-graphite reactors producing 1000-2000 MWe by 1965. Five industrial consortia were formed to fill the expected construction orders. The AEA began to turn its attentions to the development of the more efficient advanced gas reactor (AGR). The aftermath of the Suez crisis, the government revised its reactor MWe estimates up to 5000-6000 by 1965, an increase of at least 250%, without increasing the number of nuclear reactor stations. In 1959, British nuclear optimism reached a peak when reactor orders were received from Japan and Italy.

By the early 1960s, however, the blush was beginning to fade from the British nuclear rose. The energy crisis of the late 1950s had waned and the industrial consortia lacked sufficient orders to remain in business; by 1962, the five consortia were reduced to three. The economics of the gas-graphite reactor, especially in competition with coal, were not as impressive as originally projected. So, in 1964, a government White Paper ordered the AEA to standardize on a new, more efficient reactor technology. The AEA quickly narrowed the alternatives to the British-developed AGR and the American BWR before choosing the British design. The choice was a contentious one, open to charges of "nuclear nationalism," especially in the face of the contemporary New Jersey Central analysis of its Oyster Creek BWR.

The British nuclear industry continued to founder. In 1967, the three nuclear construction consortia were reduced to two, each heavily subsidized by the government. Serious development problems delayed the construction of the ordered AGR, and critics were voicing strong attacks against the AEA for placing all its research efforts on one technology and for excluding industry (see Burn, 1967: 87, 113). While the particulars of Burn's criticisms were open to dispute, the charge that the British nuclear reactor RD&D program had been unable to produce an economic and technically efficient reactor was unarguable.

In 1973, the remaining nuclear construction firms were consolidated. Later that year, the CEGB published a report calling for the AEA to import the American PWR in light of continued trouble with the AGR, a choice seconded by the lone remaining British nuclear construction firm. But, again, in 1974, the AEA chose a British designed, steam-generated, heavy water reactor (SGHWR) over the proven PWR. Disregarding the technical and economic uncertainties presented by the SGHWR, the Labour government refused to "sell short on the nuclear technology in which all British governments have invested heavily since World War II" (Walsh, 1974: 511). Faced with increased development difficulties with the SGHWR, the CEGB has continued to argue that it be permitted to purchase an American PWR (Hawkes, 1978: 755-756). There can be little doubt, then, regarding the failure of the British nuclear reactor RD&D program to develop and disseminate an indigenous reactor system, a failure that is even more stark in light of the early British nuclear leadership.

In many ways, the French program closely parallels the British experience. The major difference is that French atomic scientists did not have a national nuclear arms program to shape their early research. However, the collaboration of individual French scientists in the British and Canadian wartime research, combined with the early emphasis in French nuclear research on developing a nuclear weapons capability (see Scheinman, 1965), largely obliterated this distinction between the French and British programs.

The major institutional actors in the French nuclear reactor development program were the Commissariat a l' Energie (CEA), created in 1946 and given complete responsibility for all nuclear development programs, Electricite de France (EdF), the nationalized French electric utility, and, at a later date, French industry.

Like the British, the weapons-dictated preference for plutonium and American refusal to provide enriched uranium forced French nuclear technicians to design a gas cooled, graphite moderated, natural uranium reactor. The first French reactor, like Calder Hall, was built to produce both plutonium and electricity. Opened in 1956, Marcoule 1 was only rated at 3 MWe and was used exclusively as a plutonium-producing facility. In 1959 and 1960, Marcoule 2 and 3, identical 40 MWe gas-graphite reactors, went critical. In 1955, the CEA authorized the construction of larger demonstration reactors, and in 1962 the 70 MWe gas-graphite reactor at Chinon became operational; its larger 240 MWe neighbor was opened in 1965. Both Chinon reactors were built under the supervision of the CEA but operated by EdF.

During the late 1950s and early 1960s, the EdF and some French industrial construction firms began to question the wisdom of continued dissemination of the French gas-graphite reactor. In 1960, the EdF agreed to build and operate an American-designed 319 MWe PWR in conjunction with the Belgian government. Still, the CEA maintained its institutional hegemony in the French nuclear reactor RD&D as it worked to improve upon its gas-graphite technology; in 1967, it opened Chinon-3, a 500 MWe facility, and in 1969, St. Laurent-1, which was reported to have "attained technical and economic levels at which competitiveness with fossil-fueled systems can emerge " (Hirsch, 1966: 938).

However, by 1967, the EdF and the emerging French nuclear industry began to lobby strenuously and publicly against the gas-graphite reactor. The EdF cited the major cost breakthroughs experienced by the American reactor models in the previous few years while French industry nuclear industries "saw themselves becoming technologically isolated and foreclosed from competing successfully for sales abroad" (Walsh, 1976: 340); both pointed to the West German adoption of the American LWR technology as proof. The issue was debated at the highest levels of the French government, and, in 1967, the deGaulle government announced that France would continue to build its gas-graphite reactor, although the CEA was ordered to participate in building a second PWR with the Belgian government, a 725 MWe facility in Tihange.

Still, the issue did not abate. In 1968, the major French advisory committee on nuclear reactors issued reports calling upon the CEA to cease building gas-graphite reactors until their relative efficiency and economics could be accurately assessed and to build at least one commercial-sized LWR. In 1969, another report was issued which explicitly recommended the construction of four or five French LWRs (ranging in size from 700-900 MWe) by the end of 1975.

In late 1969, President Pompidou announced that the French government would sponsor the construction of an LWR built on license from either Westinghouse or GE. Furthermore, a committee was established to investigate the responsibilities of the CEA in French nuclear RD&D programs. Pompidou's announcement clearly indicated that the EdF and its industrial allies had won the institutional struggle with the CEA over the dissemination of the French reactor program. French industry, responding immediately to the decision, began to vie for American licenses, with Framatome and the SOGERCA consortium receiving licenses from Westinghouse and GE, respectively. In 1970, Framatome was awarded the first French LWR contract, a 900 MWe PWR at Fessenheim; in 1971, Framatome was given contracts for three additional PWRs. Thus, by the early 1970s, the French reactor industry had adopted a reactor for dissemination, even though it meant rejecting the product of its domestic RD&D program. As Walsh later commented, "The ultimate decision by the French government on nuclear industry can be seen as a victory for pragmatism over economic chauvinism" (Walsh, 1976: 340).

The Analytic Perspective

Viewing these different national nuclear reactor development programs from the perspective of the comparative analytic framework permits us to make some important observations that might not otherwise be as apparent if each were treated as an isolated case study.

First, the relationship between the developmental stages and the multiple objectives must be stressed. For the majority of the national RD&D programs, the three different developmental periods were characterized by a shifting priority of objectives. Each nuclear RD&D program, for instance, was initiated with explicit statements from government officials how the research was important in terms of national prestige and for basic scientific knowledge. As the RD&D continued, these expressions disappeared as other objectives grew more important, especially the efficient technology objective as the reactor approached the dissemination decision. Those nations whose institutions obstructed this transition of objectives experienced great difficulty. The British nuclear establishment failed to produce a competitive reactor system, partially because matters of national prestige were still weighing heavily in its objective function 30 years after its original decision to build power reactors; France, in the late 1960s, barely escaped a similar situation.

Second, the three developmental periods may be generally characterized as representing the changing leadership of the technology delivery system members. The development period was typically dominated by the developer or the government research establishment, the demonstration period by the vendor or nuclear industry, and the dissemination stage by the consumer, in this case, the electric utility industry. These actors would manifest their different organizational objectives. For example, the developer/government might be more concerned with political equity than the development of an efficient technology while the consumer/utility, emerging at a much later stage of development, would have just the opposite priority. If the description of the changing lead organizations and their rankings of national objectives is correct, then one might conclude that the development and dissemination process is less a case of a developing technology and more one of interorganizational conflict. The development and dissemination of power reactors was relatively uneventful in those nations where the appropriate institutional actors exercised leadership during a given phase of the development and the transitions between the three phases were fairly smooth (i.e., one found an "integrated" TDS). Serious problems occurred in the U.K. and French developments programs where an institutional actor retained control of the program after a developmental transition (i.e., an institutional transition) should have occurred.

In Section II, the national objectives were defined in terms of technology development attributes. It is therefore necessary to review the surveyed national nuclear RD&D programs to determine which attributes were most critical in determining the different objectives.

The key attribute in defining and supporting Science for Science's Sake was, not surprisingly, the presence of an active scientific community, the group that stood most likely to reap direct and immediate gains (both in terms of money and peer recognition) from this objective. The perceived importance of being an early starter is another attribute contributing to this objective, because this objective suggests being in a technology's vanguard. Still, even West German government, which was not an early starter, cited the importance of this objective. Finally, the presence of a concomitant military research program seemed to contribute to this objective, not because the ends were necessarily identical or even compatible, but because there were spillovers from the military research during the formative stages of the civilian technology development. Also, of course, the presence of a military program means the availability of a trained cadre of skilled scientists and technicians and, quite often, needed financial assistance.

At best, National Prestige is an elusive objective from both the definitional and attainment standpoints, which makes it difficult to state which attributes were the most significant in contributing to its successful achievement. The resources invested have an interesting effect on a development if national prestige is an objective. During the early stages of a development, national prestige can be garnered with a small investment; basic research is relatively inexpensive. However, this investment can have the effect of binding the nation's prestige to the technology development, thereby inhibiting the government from abandoning the project should it later prove technically or financially unrewarding. In short, the initial resources invested for achieving the national prestige objective could be quite low, but the political sunk costs they incur can outweigh the later economic analysis of sunk costs and marginal costing. Other attributes that appeared to contribute to the prestige objective in the context of nuclear reactor RD&D were the presence of a concomitant military research program (reactors seemed to reinforce the great power status conferred by nuclear weapons) and the national R&D heritage (which most nations were determined to maintain or reestablish).

The Development of an Efficient Technology was most fundamentally affected by the presence of an Integrated TDS. The United States and Canada are the best examples of the cooperative developer/vendor/consumer relationship and smooth transition between these actors. The West German reactor development program did not make significant strides towards the reactor dissemination until the reticent central government began to fulfill its TDS responsibility. The ultimate failures of the French and British programs to produce domestic reactor systems were institutionally characterized by the lack of cooperation and integration among the TDS actors. Clearly the level of resources invested was an important element in achieving an efficient technology, but it is difficult, if not impossible, to determine from this sample of cases what the necessary level might be. The British and French invested a great deal more than the Canadian program but were noticably less successful. The West German nuclear RD&D program was underfinanced until the federal government started to contribute heavily. Finally, it appears as if the development of multiple technology options was the most effective manner to attain an efficient technology, but the Canadian success in developing only one reactor technology must inject a word of reservation here.

Finally, the Political Equity objective was represented by the presence of competing groups, such as the presence of the active scientific community (especially during the early R&D period), the integrated TDS, and the multiple technology options. The last in particular can be depicted in terms of competing interests. Perry (1976: 82-83) speculates that the multiple reactor technologies developed in the United States program were more a function of rival research institutions than technological uncertainties; similar evidence may be found in the Soviet program.

IV. POLICY OBSERVATIONS

These analyses can be reformulated in terms of a number of policy observations which can be applied to other technology developments and may also be used as a surrogate measure to evaluate the utility of the proposed analytic framework.

First, different organizations and their objectives are particularly critical or even predominant at certain stages of the development and dissemination processes. Second, different attributes are essential for the achievement of different objectives; for example, an integrated TDS was seen to be central to the efficient technology objective but less so if science for science's sake or national prestige were the motivating objectives.

These two observations suggest that is is extremely important for the participants in a technology development to recognize what stage the program is in and what are the appropriate attributes and objectives given that stage. This observation is not as obvious as it might appear. The early British and French programs were directed towards building a functioning reactor system as quickly as possible because the British needed to develop an export commodity, and both nations wished to guard against a perceived energy shortage. The emphases placed on these efficient technology goals during the development period caused both national programs to stress objectives that were inappropriate at that time. A similar observation may be made regarding the apparent British government decision to place national prestige above efficient technology during the later stages of the English reactor development program.

Third, these cases affirm the importance of viewing technology development programs as having multiple actors and objectives, which means that a single evaluative metric for a technology development program is inadequate and potentially misleading. The British persistence in building an indigenous reactor system would be inexplicable in terms of the efficient technology objective but would be more plausible if one posits that the government chose to emphasize the national prestige and political equity objectives over the development of an efficient technology. The policy implication is clear: a technology development must be measured against a number of objectives, and the ultimate assessment of its "success" or "failure" must reflect that multiplicity of objectives. Furthermore, the recognition of multiple objectives should alert the policy researcher that technology developments might be responding to objectives not included in the analyst's list.

Fourth, these cases all demonstrate that the costs of a technology development grow greater as the development progresses and, in an apparent contradiction to conventional wisdom, as the early technology uncertainties are resolved. The reactor dissemination stage was the most expensive; Westinghouse and GE, who were both convinced that the requisite reactor technology was well practiced and that sizeable profits were imminent, are estimated to have lost over $750 million on their 12 turnkey reactors by grievously underestimating the remaining cost and technology uncertainties (Perry, 1976: 99). This finding replicates the SST development experience, virtually all mass rapid transit systems, and a large sample of commercial developments reviewed by Scherer (1970).

Fifth, the successful development and dissemination of an efficient technology was largely determined by the cooperative and continued involvement of the developer, vendor, and consumer. In the case of nuclear reactors, there were many indications during the protracted developmental periods that a given investor's attitude regarding risk varied, even when there were no objectively verified alterations in the prospects for success. In such cases, an organization's sunk costs may act as a damper on risk adverse behavior, without which the development might be terminated. To ensure the consistent participation of the vendor and the consumer, the U.S. and Canadian governments insisted that they invest their corporate resources in the development, i.e., incur their own sunk costs. As posited in Section II, these sunk costs created a commitment to the continued vendor and consumer support of a program that might otherwise have flagged, especially as the reactor programs reached the expensive dissemination stage. Conversely, those national programs whose vendor and consumer organizations had little or no requirement to contribute their R&D resources (i.e., France and England) were unable to develop an efficient technology. The policy implication of this observation is that the presence of an integrated TDS must not be assumed.

The integrated TDS must not only be carefully assembled but steps must also be taken to insure the continued integrity of the TDS throughout the development and dissemination processes. (Parenthetically, the presence of an integrated TDS does not guarantee the efficient development and application of a technology; the U.S. SST was not cancelled on account of an ineffective TDS.)

It is worthwhile to examine two attributes often said to be influential in the dissemination of a new technology. The hypothesized importance of being an early starter for achieving an efficient technology, especially for export purposes, is not supported by the reactor development experiences. Britain, which operated the world's first power reactor and had the first export sales, was left far behind in the reactor export competition by the United States and, most tellingly, by the West Germans who were as late starting as the British were early. Indeed, being an early starter might have the unfortunate consequence of binding a nation's industry to an outdated technology, a condition that occurred in England and threatened in France. Obviously being on the technological frontier is not an inherent disadvantage, but the nuclear evidence suggests that it is not unambiguously advantageous. A similar conclusion might be drawn from the early British lead in jet airliners, a lead which Boeing surmounted and that the European jet industries have been unable to regain. These examples tend to confirm the hypothesis that technological innovators are not always the most successful purveyors of that technology (Scherer, 1970: Chapter 15, and Utterback, 1974) and that a national strategy predicated on "buying in" on proven technologies and then realizing profits from superior manufacturing and merchandising techniques can be a technically and economically attractive option (Gilpin, 1970).

A second attribute worth specific examination is the putative value of a concomitant military research program. Although it seems influential in the early stages of a development, its overall validity is not supported by the data. Two nations--the United States and the Soviet Union--had nuclear military research programs and successfully developed workable reactor systems; France and Britain, both of which had concomitant military research, were unable to develop an indigenous nuclear reactor system while the remaining two nations--Canada and West Germany--each developed reactor systems without any accompanying military research.

Evaluating the Analytic Framework

These policy observations permit us to evaluate the proposed analytic framework from both an intellectual and a policy perspective. Regarding the former, the most important intellectual insight of the framework is that it forces explicit recognition of multiple objectives and competing actors and that these competitions are not one-time encounters. The framework provides a concept and tool for coherently explaining a technology development in terms of the political, institutional, and economic forces that shape (either positively or negatively) a given public policy. This, by itself, is hardly unusual; a large number of case studies have illuminated similar themes. However, in the context of the six national developments of the magnitude examined here, the framework's contribution is unique and valuable. Even with the necessary reservations, evidence from different nations and technical programs can be juxtaposed and compared to obtain a general understanding of what technical and social pressures affected the development and dissemination of a civilian technology. The capability to fit disparate information into a common framework that renders plausible explanations for the entire range of the studied phenomena, then, is probably the most important intellectual accomplishment of the analytic framework.

A second feature of the framework as a heuristic tool is its ability to identify what information or data the research is lacking. The comparative feature of the construct encourages greater confidence in this regard than the case study mode. Noting how the data absent from one study enrich the other studies, the comparative analyst can discern overall patterns of data deficiencies. For example, the political equity objective, which is amply supported in the political science literature, was observed to be of only marginal importance in the ordering of objectives, which did not conform to expectations. One could logically argue that either the expectations were amiss or, more likely, the appropriate data were not available.

A final, more tentative advantage of the model is that it appears to have (or could develop) some predictive capabilities, even if only cautious ones. For instance, a nation's development of thermonuclear or breeder reactor technologies might be predicted to be problematic if its early demonstration reactors were held strictly accountable to a cost efficiency criterion. Similarly, a technology whose dissemination decision was dependent on a concurrent military program for its technology could be seen as suspect. These modest predictive claims, of course, require tempering and validation through further testing. They also are a key to the second area for evaluation, the policy utility of the analytic framework.

The framework's policy value must be judged by its capability to identify and extract policy observations out of an unstructured body of information and to minimize mistaken interpretations. Again, it appears to have been quite useful for at least three reasons. First, as defined, it permits comparisons of multiple experiences, thereby reducing the limitations inherent in a single case study. This capability protects the analyst from biasing his recommendations on a case study of a technology development that might, in retrospect, be seen as anomalous. Just as important, it permits the policy analyst to confirm a finding that might otherwise appear as unique to a single study. For example, the argument that the British Comet jet liner suffered from premature commercialization might be dismissed by skeptics who claim that other factors were more central to its failure and that one should not generalize from one example. However, the later failure of the British gas-graphite reactor gives added substance to the observation that the early commericalization of advanced technology can be a mixed blessing. In short, the policy analyst can benefit from the advantages that accrue from using a larger data set, advantages that formerly were difficult to obtain and tenuous when multiple cases were examined.

The second policy benefit of the general model is that it identifies separate developmental stages and highlights their particular demands. This forces the policy adviser to recognize that there are different periods in a technology's RD&D and dissemination, each with its own requirements, and permits him to recommend measures appropriate to those requirements.

A final policy benefit of the framework arises from its emphasis on the institutional elements of a technology development rather than the scientific or technical aspects. The evidence to date suggests that it is extremely difficult to expedite scientific research or technological developments; such efforts have typically resulted in significant cost overruns and technical deficiencies. It is perhaps more possible to encourage a development by removing or at least reducing the institutional obstacles that might otherwise impede the development and dissemination of a technology--policies that can be instituted by the policymaker--than to expedite scientific or technical development itself, which is more problematic.

These evaluations of the intellectual and policy aspects of the analytic framework do not, of course, mean that it is in its ultimate form. As discussed in Section II, it was proposed as a first attempt to understand a series of complex developments, to structure large amounts of varied information, and to describe, in skeletal ways, the logic of RD&D programs and institutions. In its current iteration, the construct is more suggestive than conclusive. The limitations contained in the definitions, the data acquisiton problems, and the restricted number of cases all indicate that important work is yet to be done before it can be considered a policy analytic tool applicable to a broader range of technology development. Obviously, such efforts require much to be done but even more remains to be gained.

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