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The Government's Role in the Commercialization of New Technologies: Lessons for Space Policy

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ABSTRACT

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Private sector interest in emerging space technologies has grown rapidly during recent years. This has been accompanied by an increased government emphasis on commercialization of these technologies. However, the transition from a virtual government space monopoly to viable private space industries is by no means inevitable. Many advocates of government support for commercialization efforts have argued that a number of obstacles, including the high capital costs associated with some space commercialization projects, the potential breakdown of private investment incentives if successful ventures can be easily imitated, and government regulatory policy, may retard private participation in space ventures.

Many of the issues that are prominent in discussions of space policy also arose during debates over alternative energy sources, nuclear power, communication satellites, the development of commercial aircraft--even the construction of a transcontinental railroad. This paper draws upon the history of technology development in three of these industries to assess the importance of obstacles to commercialization and to evaluate the success of earlier government policies. The lessons drawn from these case studies suggest caution in extending government support for commercialization of space technologies.

Private sector interest in emerging space technologies has grown rapidly during recent years. While this is particularly apparent in the burgeoning commercial satellite industry, private activity extends much further. A number of companies are developing technologies for materials processing in space under joint endeavor agreements with NASA; the transfer of expendable launch vehicles (ELVs) and earth observation/ remote-sensing satellites from public operation to private operation is already underway; and one company has expressed interest in replacing Challenger by a privately owned and financed orbiter. Accompanying this expanding private sector interest has been an increased government emphasis on commercialization of space technologies.[1] This is likely to be reinforced by federal budgetary pressures, combined with extensive shuttle re-design costs in the wake of the Challenger accident, which may curtail available NASA funding and enhance the attractiveness of private sector financing of space technologies.

The transition from a virtual government space monopoly to a viable commercial space industry is not inevitable. Many advocates of government intervention in the commercialization of space technologies have argued that a number of obstacles retard private participation in space ventures. These include the high capital costs associated with some space commercialization projects, the potential breakdown of private investment incentives if successful ventures can be easily imitated, and government regulatory

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[1] See, for example, President Reagan's National Space Policy, announced on July 4, 1982 and Space Commercialization Policy announced on July 20, 1984, and the Commercial Space Launch Act and the Land Remote-Sensing Commercialization Act of 1984.

policy. The appropriate government policy toward commercialization of space technologies depends upon the importance of these and many other factors.

If, when, and how the government should intervene in the development of private markets are questions with a lengthy pedigree in regulatory economics. Many of the issues that are prominent in current discussions of space policy also arose during debates over alternative energy sources, nuclear power, communication satellites, and the development of commercial aircraft. There are even strong parallels in the controversies over federal support for the construction of a trans-continental rail network and the use of public capital in canal construction.

This paper evaluates a number of the economic arguments which have been advanced to justify government intervention in space commercialization. Section I discusses three such arguments: capital market failure, non-appropriability of prospective returns, and the need to correct government-induced distortions. The remainder of the paper draws upon the history of technology development in a variety of industries to assess these arguments and draw out lessons for government involvement in the commercialization of space technologies. Section II focuses on three particular technologies: commercial aircraft, nuclear powered reactors, and communications satellites. It explores the government's role vis-a-vis the private sector in the development of these technologies. Section III uses the lessons of these earlier programs to develop guidelines for national commercial space policies and for successful government commercialization programs more generally.

I. Economic Rationales for Government Intervention

This section presents classical micro-economic arguments for government intervention in the development of commercial technologies. This approach presumes that, absent specific imperfections, private markets can be trusted to allocate resources efficiently-- that is, in such a way as to maximize total welfare. The classical economic rationale for government intervention in private markets therefore hinges upon identifying some imperfection or market failure.

Efficiency goals certainly are not the only motivation for government intervention. In space policy as in many other areas, political goals such as "national prestige" or "leadership" and "international competitiveness" often dominate policy debates. Economists have no particular expertise in directing policies that are to be pursued for prestige reasons, however, nor is pursuit of such political goals necessarily compatible with the objective of developing efficient commercial markets. Given these considerations, and because many of the arguments for space commercialization policies are couched in terms of shortcomings or failures of private markets, my discussion concentrates on possible efficiency rationales for government intervention.[2]

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[2] I focus exclusively on private, as opposed to public or collective, goods and services. Private goods satisfy two conditions: (1) Consumption is exhaustive: if I consume the product, it is unavailable for your consumption. (2) Consumption is exclusive: if I purchase and consume the product, I can exclude you from also consuming it and receiving its benefits. When consumption is neither exhaustive nor exclusive, the private market will tend to undersupply the good relative to the socially optimal level. Although public goods such as national defense are an important cause of market failure, the standard solution to this type of failure is public provision. My focus on commercial markets therefore rules out these types of goods.

In addition, although this section focuses on imperfections in the operations of private markets, it does not imply that market imperfections *ipso facto* warrant government intervention. Government policies are seldom perfectly constructed or implemented, and they typically introduce a new set of distortions into market operations. Imperfect markets must therefore be balanced against imperfect government. This suggests a higher standard for government intervention than a simple "market failure" test.[3]

Three market failure arguments are typically invoked to justify government intervention in the development or commercialization of space technologies.[4] These are: (1) the inability of private capital markets to finance development of the new technology; (2) non-appropriability of the benefits of private R&D or innovations; and (3) distortions caused by pre-existing government policies or regulations that interfere with development of the new technology. I analyze each of these in turn.

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[3] See Schmalensee (1980) and Eads (1974) for more general discussions of this point.

[4] This is not an exhaustive list of possible causes of market failure. In particular, it excludes monopoly power, or imperfect competition. While this may be one of the dominant causes of market failure generally, it is rarely used to justify government intervention in technology development. A notable exception is the communications satellite industry, which is discussed in detail in section II.

1. Financial Market Failure

One of the most common arguments for government intervention in commercialization activity is based on the inability of the private capital market to provide necessary financing. This argument typically relies on the presence of three factors:

(i) High uncertainty or risk

(ii) Large fixed costs

(iii) Long lead times for project development or long payback periods.

These factors may reduce or eliminate the availability of private financing for space commercialization. There are two central issues in evaluating this argument for government intervention. First, are space technologies characterized by these factors? Second, can the capital market finance projects with these characteristics? These issues are addressed below.

A. Characteristics of space technologies. The commercial development of space technologies involves the factors described above in varying degrees. Uncertainty is the dominant factor, common to virtually all space technologies. It takes several forms. There may be technological uncertainty: for example, what is the expected launch failure rate for a particular ELV. Market uncertainty may surround both the potential demand for new products and the costs of these products. For example, how much more are customers willing to pay for the capabilities of gallium arsenide semiconductors; what is the variance around the initial cost estimates of production; by how much are these costs likely to change under various scenarios. Finally, there may be uncertainty about the future economic environment, and in particular, about future government policies. The expected profitability of a commercial expendable launch vehicle (ELV) industry, for example, depends upon the government's shuttle pricing policy. Materials processing in space (MPS) will be strongly affected by government Space Station policies.

Expected costs and lead times for project development of space technologies vary greatly. On the one hand, cost estimates for a replacement orbiter are $1.5 to $2.4 billion;[5] for building a fleet of ELVs, as much as $1.0 billion.[6] On the other hand, McDonnell Douglas estimates the cost of developing a materials processing technology to the production prototype stage at $15 to $75 million, exclusive of transportation.[7] These and similar projects involve lead times of two to ten years or more. MPS and other projects that rely on the availability of space station labs for commercial production face potentially longer delays as space station operation schedules slip. However, while these costs and lead times are not trivial on an absolute scale, they are not particularly high relative to those of other large-scale or high technology projects discussed below.

Although space technologies may exhibit some of the characteristics argued to impede the availability of private financing, this varies

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[5] The Congressional Budget Office has estimated the cost of a replacement orbiter at $2.4 billion over the next four years. General Space Corporation, which is pursuing the possibility of a privately-financed replacement orbiter, uses an estimate of $1.5 billion. Both estimates exclude the initial Shuttle development costs, as well as redesign costs resulting from the Challenger accident.

[6] NASA estimates, as reported in Flight International, 29 March 1986, p. 29.

[7] See Kurt P. Johnson's presentation, "Perspectives on Material Processing in Space," at the Explorations in Space Policy Symposium.

considerably across technologies. Most importantly, relatively few projects rank high on all three characteristics. MPS projects, for example, typically involve substantial technological and market uncertainty. However, the costs of developing the technology to a prototype stage are relatively small. Construction of ELVs, in contrast, requires much higher investments but involves less uncertainty and shorter lead times. This association is not entirely coincidental. In general, investments to reduce uncertainty at the early stages of technology development tend to be relatively small. Higher capital requirements are associated with commercial production, when much of the initial uncertainty has been resolved.

B. Capital Market Operations. Economic analysis suggests that the merits of the capital market failure argument typically are overstated.[8] Although commercial development of many space technologies may require multi-million dollar investments, the projects are well within the capacity of the private capital market. Pharmaceutical firms invest roughly $1 billion annually in R&D on new drugs, despite highly uncertain and distant returns. IBM's System 360 development and production involved nearly half a billion dollars in R&D and risked $5 billion, a "bet the company" gamble, on a highly innovative computer design.[9] The explosion of Silicon Valley semiconductor and computer enterprises, and the rapid development of

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[8] See Neil Doherty's paper on "Insurance, Risk Sharing, and Incentives for Commercial Use of Space," in this symposium for a broader analysis of the capital market's role in commercializing space technologies.

[9] T. A. Wise (1966).

biotech/genetic engineering firms attest to the willingness of private investors to finance high risk ventures in emerging technologies.

The capital market also finances such activities as construction of baseload electric generating units, chemical processing plants, and oil refineries, production of liquified natural gas supertankers, and even construction of the Trans-Alaska pipeline--all of which involve hundreds of millions of dollars, and as much as a decade or more before commercial returns are realized. The cost and risk of space ventures may put them beyond the capacity of smaller firms,[10] and joint ventures or other forms of cooperative financing may be desirable to spread risks, but the projects do not appear unique among private sector ventures. There is no evidence that the capital market systematically fails to finance profitable ventures because of high fixed costs, long lead times, or project risk.

This is not to say that the capital market would be *willing* to finance development of all space technologies. The three factors described above all tend to lower the present discounted value of profits for a project. Private investors will provide capital only if the expected risk-adjusted returns are commensurate with the returns available on alternative investments. Projects with a low probability of commercial success will be financed only if the profits when successful are quite high. Technologically promising projects may be passed over by the private market, for investors are interested in commercial profitability, not in engineering accomplishments *per se*.

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[10] Although a vast number of small firms currently are engaged in exploring commercial development of space technologies.

This is not a failure of private financial markets, but a virtue. If investors decline to finance a project because there are more productive uses of their capital, then the government reduces total social product if it intervenes to get the project financed.[11] It also risks being saddled with a commercial "white elephant." Intervention would be desirable only if the government were better at "picking winners" than is the private sector. The government's record in this respect is far from convincing, as is discussed in Section II.[12] This suggests that arguments for government-financed development based primarily on alleged capital market failures should be viewed with strong skepticism.

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[11] Unless there is some market imperfection that creates a wedge between private and social benefits. See, for example, the non-appropriability discussion following this. In this case, government intervention might be warranted, though not because of capital market failure.

[12] Studies of technology development across a wide range of industries also reach this conclusion. See Eads (1971), Baer et al. (1977), Krugman (1984), Nelson (1982, 1984), and Nelson and Langlois (1983).

2. Non-appropriability

The second argument for government intervention arises from potential non-appropriability of the benefits of private research and development or investment. The central idea underlying this argument is that successful techniques or products will be imitated, so that a firm discovering a new technology will share its benefits with other firms. If a private firm expects to bear all the costs of its investment and realize only a fraction of its total benefits, it will tend to invest less than the socially optimal amount in the project. This inefficiency arises because of "externalities," divergences between private and social costs and benefits.

The more important potential sources of non-appropriability for emerging space technologies are:

(i) Technology spillovers from non-patentable results of basic R&D.
(ii) Technology spillovers from industry-wide learning-by-doing.
(iii) Industry-wide learning about costs.

I discuss each of these below.

Technology spillovers arise when technological innovations or information developed by one firm also benefits other firms. Basic research is a classic example of this phenomenon. Results of basic research may have a broad range of possibly distant applications: for example, the Project Hindsight study commissioned for the Department of Defense noted that the origin of many successful innovations could be traced to research results developed as much as 20 years earlier.[13] In addition, results of basic research may be difficult to sell or patent.

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[13] See Isenson (1969).

Patent laws, which give the inventor property rights to his invention, are an attempt to improve the appropriability of investments in new technologies. However, because the results of basic research are not directed toward a particular application, they may not involve a patentable process or product. Without clear property rights to the findings, firms may find it difficult to obtain compensation from future users.

Such arguments are used to justify government support of basic research across a wide range of fields. They appear to be validated by the concentration of basic research in government-sponsored labs or academic settings; relatively little basic research is conducted by industry. As one moves away from basic and toward applied research or development, however, more of the benefits of the research become appropriable. The links between research results and final products strengthen, and the ability of firms to enforce property rights to their results improve.

A second source of technology spillovers is industry-wide learning-by-doing. If a firm can improve its technology or lower its costs by observing another firm's experience, it has less incentive to invest in obtaining experience itself. In many high-technology industries, experience-related cost declines are significant. If industry-wide learning economies are large relative to the firm-specific learning economies, this non-appropriability may deter private development of the technology. Similarly, if innovations diffuse rapidly through an industry, then each firm has less incentive to invest in innovations, because they can "free ride" off others' investments. The importance of these effects varies substantially across different technologies and market structures.

Finally, learning about costs can lead to non-appropriable benefits at the commercialization stage of technology development. If technologies are not proprietary and costs or market conditions are uncertain, then firms may have an incentive to let someone else make the initial investment to discover whether costs are within a commercially viable range. This depends critically upon technologies being non-proprietary, and on there being no substantial first-mover advantage in the industry. If, for example, the first firm to develop a technology enjoys marketing advantages over later entrants, or if imitative entry takes a long time, this may overcome the disincentive created by non-appropriability of cost information.

Analysis suggests that the rationale for government research subsidies or direct government-sponsored research is strongest for basic research and weakens as the technology moves toward development and commercialization stages. Since many of the space technologies currently being discussed are well into the applied research or development stages, the importance of non-appropriable gains is questionable. Some technologies--such as expendable launch vehicles and particular applications satellites--are at the commercialization level. At these later stages, firms typically are better able to protect most of the gains from their investments. Industry-wide learning effects may mitigate this; their importance is an empirical question that can be answered only by careful analysis of the technological characteristics and industry market conditions of the specific technology being considered.

3. Government-induced Distortions

The third justification for government support of emerging technologies is based on the need to compensate for government policies and programs that discourage private sector investment. This is a "second best" argument: while unassisted private development of new technology may be efficient in ideal markets, existing markets fail to satisfy that ideal because of pre-existing government distortions. Policies to compensate for them are required to promote efficient levels of investment.

Government-induced investment disincentives can arise from a variety of sources. I focus on three in the discussion below:

(i) Economic regulation

(ii) Government competition

(iii) Uncertainty over future policy

These cover a broad, though not exhaustive, range of government activities.[14]

The most pervasive source of government distortions is likely to be administrative restrictions and regulations, including economic regulation. A frequently cited obstacle to development of commercial expendable launch vehicles is the maze of administrative requirements and licensing procedures that must be satisfied, increasing costs and delays. Economic regulation of industries related to particular space technologies may have subtler, but more substantial effects on investment incentives. For example, Food and Drug Administration regulation of pharmaceuticals may reduce the

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[14] Antitrust policies are also frequently cited as a source of investment disincentives, arising from their restrictions on joint ventures or consortia. These may reduce private investment in new technologies by limiting firms' abilities to spread risks or pool capital. The importance of this problem seems substantially reduced by the 1984 National Cooperative Research Act.

profitability of space-based drug manufacturing. Federal Communications Commission (FCC) allocation of geostationary orbit "slots" and procedures for spectrum allocation to communications satellites appear to have shifted technology development toward excessively hardware-intensive satellite R&D.[15]

Although government regulations may change private incentives, they do not necessarily discourage private investment. The predicted effect of regulations depend upon the particular circumstances and conditions of the industry being considered, and interactions between different types of regulations may have unexpected consequences. For example, natural gas wellhead price regulation discouraged producers from investing in natural gas exploration during the 1960s and early 1970s. However, price regulation of natural gas distribution companies encouraged pipelines to invest in more expensive liquified natural gas and synthetic natural gas supplies.[16] The precise form of a regulation can be critical: in the area of air pollution control, emissions limits that are formulated in terms of engineering standards, which specify the control technology that must be used, discourage investment in emissions control technology. Limits that are formulated in terms of tradeable rights with overall limits on emissions levels tend to encourage investment in control technology. Regulations may even induce socially excessive investment levels, as in the case of agricultural price supports.

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[15] See Macauley (1986).

[16] This occurred because retail prices were set using "rolled-in," or average cost pricing schemes, under which high cost gas was averaged in with lower cost supplies. For a discussion, see Thomas Stauffer's chapter, "Liquified and Synthetic Natural Gas--Regulation Chooses the Expensive Solutions," in Caves and Roberts (1975), pp. 171-198.

Second, potential government competition with private industry may alter investment decisions. This problem arises infrequently in the U.S., due to the government's historic aversion to public ownership of industry. In the few industries in which public and private firms co-exist, they rarely serve the same market. For example, although the electric utilities industry consists of both public and private firms, most operate as local monopolists in distinct geographic markets.[17] This serves to reduce, but not eliminate, debates over "unfair government advantages" in electric power.

In space transportation, however, this debate assumes critical importance. The primary competition for a U. S. commercial ELV industry is likely to be NASA's Shuttle, followed closely by foreign ELVs. With ELV launch costs bracketed by Shuttle variable launch costs on the low side, and Shuttle long-run marginal costs on the high side, expected Shuttle pricing policies are crucial to the decision to invest in an ELV fleet.[18] If the government prices Shuttle services below their opportunity cost, ELV

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[17] Some utilities have overlapping service areas that may give rise to public power v. private power conflicts. Given the substantial size advantage most private utilities have over typical publicly-owned utilities, the issue of unfair competition or "price squeezes" tends to be raised by the latter group. There are, however, continuing conflicts over preferences given to publicly owned utilities in access to low-cost hydroelectric power. Federal power projects, such as the Tennessee Valley Authority, have also generated substantial controversy at various times.

[18] The difference between the two cost measures arises from the treatment of capital costs. See Michael Toman and Molly Macauley, "No Free Launch: Analysis of Space Transportation Pricing," in the Explorations in Space Policy symposium.

Shuttle manifest policies are also quite important, since the cost to customers of using a particular launch vehicle depends not only on the price of launch, but also on opportunity costs incurred by launch delays. In addition, current proposals to eliminate commercial cargo from future Shuttle manifests would make the pricing issue irrelevant.

investment may be too low. On the other hand, if the government adopts an "umbrella" pricing policy, setting Shuttle prices above opportunity costs in order to support higher prices for ELVs, it may encourage excessive investment in ELVs.

Finally, uncertainty over future government policies may discourage investment by increasing risk to private firms. The effect of uncertainty depends on its form. If future policy changes were random--that is, as likely to increase the future profits from the investment as to decrease them--then the uncertainty should have little impact on private investment decisions. However, if future policy is expected to reduce the profitability of successful investments in a systematic way, it may deter investment. For example, if the government is expected to raise Shuttle prices if materials processing in space turns out to be profitable, then the government truncates the upper end of commercial returns on MPS investments, lowering their expected value, and reducing incentives to undertake them.

Although these factors may distort private investment incentives, they do not inevitably imply the need for government support of technology development. Eliminating the original distortions is a more effective government response than adding an additional layer of countervailing distortions, especially given the difficulty of determining how various policies may interact. Even when the original source of government disincentives cannot be eliminated, the argument for additional intervention must be carefully analyzed. If the distortion is not substantial, it may be best to do nothing. As noted earlier, government intervention is not costless, and may have unexpected consequences through interactions with existing regulations. If a decision is made to go ahead with a new policy, it should be designed explicitly to minimize additional distortions. For example, an output subsidy is likely to be less disruptive to a market than direct support of a particular production process or technology. The former stimulates production without interfering in the market's choice of technology; the latter affects the choice of both output and technology.[19] Finally, policies cannot be analyzed piecemeal. A particular regulation may discourage investment, but the net effect of a system of regulations and policies may be to encourage excessive investment. Instead, the entire policy environment must be analyzed as a system, to avoid interventions that exacerbate existing distortions.

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[19] The intuition here is that an output subsidy promotes production of a particular product, but leaves private firms free to choose the most cost-effective production technology. Subsidies for specific technologies alter both output and technology choice decisions. Schmalensee (1980) discusses this at further length in the context of energy policy.

II. Previous Commercialization Programs

Government promotion of new technologies is not a novel phenomenon in the U.S. In 1843, Congress appropriated funds for a demonstration of Samuel Morse's telegraph system between Baltimore and Washington, D.C. Its successful completion and operation led to the commercial expansion of telegraph service throughout the U.S.[20] The development of a national railroad system in the nineteenth century was accomplished with a variety of subsidies: federal loan guarantees of railroad bonds, low interest loans, and land grants all were used to promote the rapid completion of a transcontinental rail network. The National Advisory Committee for Aeronautics (NACA), formed in 1915 to "investigate the scientific problems involved in flight and to give advice to the military air services and other aviation services of the government,"[21] contributed substantially to the development of new airframe and engine designs during the 1920s and 1930s.

Although government intervention in technology development is widespread, it is not always successful. Federal programs to develop commercially feasible alternative energy sources--coal gasification, shale oil, and other "Synfuels" projects--have floundered, even in the high energy price environment prevailing through the early 1980s. Despite more than $700 million in U.S. government support for the development of the supersonic transport (SST), it was never built. The only commercially operated

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[20] This example is taken from Baer, Johnson, and Merrow (1977), p. 950.

[21] Statement of Joseph Ames, first chairman of NACA, in 1925. Cited in Phillips (1971), p. 121.

supersonic plane--the Concorde--relies on extensive operating subsidies from the British and French governments.[22] The Clinch River breeder reactor program, after $1.5 billion in federal funding and years of criticism, was cancelled in 1983.

This section examines the development of three industries that may offer parallels to emerging space technologies. I first examine the evolution of commercial aviation technology in the U. S., from the appearance of the first commercial airliners through the government's abandonment of the SST project. I next discuss the development of commercial nuclear power, beginning with the Atomic Energy Commission's Power Reactor Demonstration Program (1955 - 1963) and extending through the early stages of private commercial construction in the mid-1960s. The final case study explores the initial development of the communications satellite industry during the early 1960's. The analysis focuses attention on the government's role in each of these industries, to determine whether any general principles can be deduced for predicting which types of government interventions are most likely to succeed.

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[22] Russia's supersonic plane, the TU-144, was developed concurrently with the Concorde, but was viewed as inferior.

1. Commercial Aviation:[23]

Government intervention in aviation has taken two forms. The first, federal support for research and development of aircraft technology, was initiated with the creation of the National Advisory Committee for Aeronautics in 1915. It includes federally-financed development of new aircraft technologies for military use. The second form has been economic subsidization and regulation of passenger airlines. Despite federal promotion of aviation, however, the U.S. government has avoided direct intervention in the development and production of commercial aircraft.[24]

I examine the influence of these policies during three "epochs" of commercial aviation technology: the development of early commercial airliners, 1925-1936; the creation of commercial jet airliners, 1946-1960; and the Supersonic Transport (SST) program, 1962-1971. The analysis highlights a number of points. First, private capital markets appear to have functioned effectively in financing the development of new commercial aircraft. The SST is the exception to this, and the private sector's reluctance to finance its development appears to have been based on low expected returns rather than excessive risk or high costs *per se*. Second, non-appropriability issues do not appear to have played a major role in determining the development of aircraft technology. The relatively low cost of R&D during the 1920s and 1930s, when technology spillovers were greatest, mitigated their effect. As aircraft technology has advanced, innovations have become

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[23] This section draws extensively on Miller and Sawers' (1968) history of aviation technology.

[24] This stands in sharp contrast to most European governments, which have provided subsidies to commercial aircraft development since the industry's inception following World War I.

increasingly application specific, sharply reducing potential non-appropriability. Third, interactions between commercial aircraft development and federal economic regulation of passenger air transportation illustrate the importance of evaluating government policies as a whole, rather than focusing on particular policies in a piecemeal fashion. Finally, the government's experience with the SST project, which represented a substantial departure from its traditional role in commercial aircraft development, suggests substantial difficulties which may arise from government direction of commercial technology. These issues are addressed in detail below.

A. The Early Development of Commercial Aircraft. The National Advisory Committee for Aeronautics was created in 1915 to spur the development of aviation in the U.S. At the time of its creation and until the late 1920s, American commercial aviation lagged far behind its European counterparts. Once underway, however, American commercial aviation flourished. By 1930, U.S. airlines carried more passengers than the rest of the world combined. American aircraft manufacturers rapidly took the lead in the development of commercial aircraft, with the introduction of the Boeing 247 in 1933, the Douglas DC-2 in 1934, and the extremely successful Douglas DC-3 in 1936. These aircraft incorporated a number of innovative component designs, and were quickly adopted by airlines throughout the world. They placed American manufacturers in the forefront of commercial aircraft design and production, a position they continue to maintain.

A combination of factors appears to have contributed to this American dominance. First, the institutional environment in which American manufacturers operated appears to have been particularly conducive to commercial aircraft development. U.S. designers seemed to be less constrained by "traditional" aircraft design, relative to their more experienced European counterparts, who had been designing military aircraft since the pre-World War I period. In addition, links between manufacturers and airlines in the U.S. were quite strong. U.S. manufacturers relied on commercial sales for a substantial part of their business: between 1927 and 1937, civil sales accounted for nearly half of all airplane and engine sales in the U.S., and perhaps an even greater share of manufacturers' profits.[25] Many of the larger manufacturers also shared common ownership with one or more airlines.[26] These conditions appear to have focused manufacturers' attention on designing airliners to specifications most likely to appeal to the airlines.[27] This stands in contrast to European manufacturers, whose commercial aircraft sales accounted for a much smaller fraction of total receipts, and whose success in military aircraft failed to carry over to their commercial planes. The inability of many European firms to coordinate designs with the technological and economic needs of the airlines proved to be a substantial block to commercial sales.

Government policy also contributed to American manufacturers' commercial success. Federal support of research and testing included both the extensive "generic" research and testing program conducted by NACA and "specific" military research and procurement. Although the relatively low

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[25] Commercial sales over the period totalled \$135.7 million for airplanes, \$75.5 million for engines, for 46% of total sales. See Miller and Sawers (1968), p. 52.

[26] This practice was later prohibited by the Airmail Act of 1934.

[27] For example, Douglas developed the DC-1 prototype, modified and produced as the DC-2, in direct response to a request by TWA. The DC-3 was in part a response to a request by American Airlines.

cost of experimentation and development encouraged extensive private R&D during these early years, this federal support substantially enhanced the availability of aircraft innovations. There was relatively little public or private American invention during the 1920s and 1930s, in the sense of *de novo* designs. However, there was extensive innovation, in the sense of diffusion of previously discovered designs. NACA fostered this through its tests of various component designs' feasibility and efficiency.[28] Military research, particularly on engine design, also contributed to the development of commercial aircraft,[29] although there was no "natural progression" from military aircraft design to development of related commercial aircraft during this period. Technology often flowed in the reverse direction; for example, commercial designs for the Douglas DC-1, DC-2, and DC-3 were later incorporated into military spin-offs.

Finally, federal policies promoting the development of air passenger transportation may have indirectly encouraged commercial aircraft development, by enlarging the potential market for new airliners. Prominent among these early policies were airmail subsidies to commercial airlines.[30]

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[28] NACA wind tunnel tests of the efficiency and practicality of cowled radial engine designs, research on engine placement, wing design, and stressed-skin metal coverings are cited as important contributions to aircraft development. See Miller and Sawers (1968), pp. 62-68, and Phillips (1971), pp. 115-121.

[29] Army research was instrumental in the development of air-cooled radial engine designs that were capable of powering commercial airliners.

[30] Federal intervention was initiated by the Kelly Act in 1925, which provided for private carriage of airmail, and by the Air Commerce Act of 1926, which directed federal development of airway and navigation systems and provided for safety certification of aircraft and pilots. Federal promotion of passenger service intensified with explicit subsidies to passenger transport provided through airmail contracts under the McNary-Watres Act of 1930.

However, the influence of these programs is easily overstated. Lindbergh's flight across the Atlantic seemed to ignite the demand for passenger airlines much more effectively than any government program of the time. Government subsidies were incomplete--a substantial share of passenger transport was carried by airlines without airmail contracts--and ephemeral.[31]

B. The Development of the Jet. The development of the commercial jet airliner owes a substantial debt to military research and development of jet engines during and immediately following World War II. The first engines to be used in the larger commercial jet airliners were products of intensive military spending.[32] Access to these technologies provided an important boost to commercial development of jet airliners. Airplane manufacturers also benefitted from their experience designing jet fighters and bombers for the military, although the construction of aircraft suitable for commercial use required quite different designs. In addition to the uncertainties associated with new commercial designs, the operating costs of jet airliners,

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[31] Miller and Sawers (1968), pp. 17-18, report that although airmail subsidy rates were high, coverage was low, with two-thirds of the passenger traffic in 1931-33 carried by operators with no airmail contracts. In addition, the McNary-Watres subsidy program was short-lived: following a scandal over contract awards, private airmail contracts were cancelled in 1933. They were replaced by minimum bid contracts in 1934, which in some cases resulted in airline subsidies of airmail transport, as bids fell toward zero. See Caves (1962), pp. 123-125.

Not until the Civil Aeronautics Act of 1938, which created a system of price, entry, and safety regulation administered by the newly formed Civil Aeronautics Administration (later CAB), were federal subsidies for passenger air transportation renewed.

[32] The British government spent an estimated £22 million ($62 million) for the initial development of the Rolls-Royce Avon engine, with a 6,500 lb. thrust. The U.S. government spent an estimated $150 million to develop the Pratt and Whitney J-57 engine, designed for 10,000 lb. thrust. Miller and Sawers (1968), pp. 156, 162.

and therefore the size of the potential commercial market, were quite uncertain. These factors suggest that, despite substantial government support for military jet aircraft, the development of commercial jet airliners involved considerable technological and commercial risk for manufacturers.

Britain took the lead in the development of commercial jet airliners, with de Havilland's decision in 1946 to develop the Comet I. This decision was encouraged by the British government, although early development limited the efficiency of the initial Comet designs.[33] Unfortunately, fatalities resulting from collapse of the pressurized cabin (due to structural fatigue) led to the 1954 withdrawal of the Comet from service. The British government intervened to prevent de Havilland's bankruptcy, and provided financial support and government oversight for re-design of the Comet. Although a modified Comet IV was introduced in 1958, de Havilland by this time had lost its lead in jet development.

In contrast to de Havilland, Boeing and Douglas decided to wait for more powerful jet engines to become available before beginning design of their jet airliners. The development of the Pratt and Whitney J-57 engine coincided with Boeing's 1952 decision to proceed with the 707 prototype. The prototype was financed by Boeing at a cost of $16 million, although the company anticipated a strong possibility of interesting the military in a tanker-transport based on its design. Boeing's gamble paid off in 1955 when the Air Force ordered a tanker based on the 707 prototype, enabling the company to cover a substantial portion of its tooling costs from defense

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[33] The decision not to wait for the more powerful engines under development restricted the Comet I to a 36-passenger plane, with operating costs triple those of comparable non-jet aircraft.

sales.[34] Douglas delayed its decision to produce the DC-8 until 1955, after Boeing had received the Air Force's tanker order. Lacking a government contract to help defray the cost, Douglas financed an estimated $300 million investment in the DC-8 itself.

The 707 entered commercial service in 1958, as did the Comet IV. The DC-8 entered service a year later. The Boeing 707 and Douglas DC-8 jet airliners were much larger, more powerful planes than were the Comets. Despite direct government assistance of more than £10 million, the Comet was not commercially competitive. Comet IV sales of 74 aircraft compare to sales of roughly 700 Boeing 707s and 400 DC-8s through 1966.

A number of features of the development of commercial jet airliners should be noted. First, maintaining a technological lead was not unambiguously advantageous. Boeing and Douglas probably benefitted from being able to observe the performance--and problems--of the Comet prior to beginning production of their aircraft. In addition, waiting for engine technology to mature allowed the U. S. firms to construct more efficient, commercially attractive aircraft.

Second, despite substantial uncertainties and relatively long payback periods, manufacturers were able to draw upon large sums of private capital to finance development of the new technology. Although commercial development benefitted from government spending on defense contracts, the federal government did not directly finance the development of commercial jet airliners. Douglas's commitment of $300 million to the DC-8 project was roughly

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[34] However, later modifications to the 707 to make it competitive with the DC-8 resulted in substantial additional costs. Miller and Sawers (1968, p. 156) report that Boeing wrote off $165 million on commercial 707 production by 1960.

equal to the firm's equity market value of $332 million in 1955, and represents a capital investment of more than $1.2 billion in 1986 dollars. This experience has been repeated in the development of the jumbo jets, and in the current development of the Boeing 767.[35] Interestingly, rising development costs have also led to new financing methods.

Third, the structure of the U.S. airline industry, and its regulation by the Civil Aeronautics Board (CAB), appears to have promoted the development of commercial jet airliners. CAB price and entry regulation restrained U.S. air carriers from competing on price, and shifted competition to service quality. This encouraged aircraft innovations that enabled airlines to offer faster service and other luxuries. Because airlines couldn't offer lower fares for lower quality service, there was an incentive for all airlines to adopt a new technology as soon as any one did so.[36] These factors suggest that a manufacturer could count on a large number of early orders for new aircraft, if the aircraft were adopted at all. This increases the return on a new aircraft, by clustering sales during the early years of production, and may overstimulate innovation in commercial aircraft design.

C. The Supersonic Transport. The federal role in commercial aviation development was drastically altered in the 1960s, with the establishment of the Supersonic Transport (SST) project under the auspices of the Federal

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[35] For example, Boeing, Lockheed, and McDonnell Douglas had invested over $500 million each in the development of the Boeing 747, L-1011, and DC-10, respectively, as of 1972. The magnitude of these development costs led Boeing to adopt risk-sharing agreements with subcontractors and airlines to finance design and construction of the 747 and 767. Carroll (1975), p. 149.

[36] There also appear to be economies of scale in operating and maintaining aircraft of a given model, which may lead airlines to make large initial orders for new planes. Carroll (1975), pp. 156-159.

Aviation Administration (FAA). The SST project embroiled the federal government in a decade-long controversy over its economic and environmental implications. It suffered a host of technological setbacks, and costs escalated rapidly. After sinking $700 million into the design phase of the project, and facing cost estimates of as much as $2 billion for construction of SST prototypes, Congress finally terminated the project in 1971.

The difference between development of earlier generations of commercial aircraft and the development of the SST is striking. The SST program provided federal direction and financing of the development of a strictly commercial aircraft; no related defense aircraft had been previously built and no specific defense applications were planned.[37] In contrast, the government's historical role in aviation development focused on basic R&D, and financed the development of new technologies only as needed for defense aircraft. The deviation from historic policy may explain many of the project's shortcomings.

The primary push for development of the SST was from the government, not from the potential users, the airlines. Promoters of the SST argued that national prestige, given the United States' dominant position in aviation technology to date, and international competitiveness, particularly once the French and British announced their collaborative effort to develop the Concorde, required an immediate U. S. project in this area. Although the SST was viewed as "inevitable," it was thought that the private market would not develop the technology sufficiently rapidly; hence the need for government intervention.

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[37] The Department of Defense viewed the project as a commercial enterprise; see Horwitch (1982a), pp. 51, 133. In addition, the Secretary of Defense, Robert MacNamera, was an outspoken critic of the economics of the SST.

Aircraft manufacturers and airlines were noticeably lukewarm about the project. Unlike the experience with earlier generations of commercial aircraft, manufacturers appeared unwilling to put much private capital at risk. From the project's inception, it was predominantly federally-funded. In fact, President Kennedy's 1963 proposed cost-sharing agreement for 75% government funding up to $750 million met with resistance from aircraft manufacturers, who called for a 90% federal cost share, and termed the proposed 75/25 split "unwise from a prudent financial standpoint."[38] Airlines appeared similarly unenthusiastic about the technology, although they eventually agreed to put up $1 million per aircraft ordered as part of a "risk-sharing" package designed to boost congressional support for continued funding in 1967.[39]

The unwillingness or inability of the private sector to fund development was attributed by SST promoters to the magnitude of the development costs, the uncertain technology and risks, and the lengthy payback period surrounding the project. Given the success of private financing for new subsonic technology, this argument appears dubious. However, the government was resistant to the signal the market had sent about the expected economics

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[38] Courtlandt Gross, president of Lockheed, cited in Horwitch (1982a), p. 65. With the initial estimates of a $1.0 billion development cost, the $250 million the manufacturers were asked to raise was certainly within the range of what they spent on subsonic aircraft development. This strongly suggests that manufacturers viewed the potential return from the SST project as much lower than the return from their subsonic investments.

[39] Although not a universally shared view, the director of the International Air Transport Association warned in late 1961: "Any government which decides an SST is necessary should face the full consequences of that decision early in the game. If they want prestige, they must be prepared to pay for it. There will not be enough airlines and enough passengers to foot the bill." Cited in Horwitch (1982a), p.23.

of the project. Acceptance of this implicit "capital market failure" argument pulled the government into a costly, and unsuccessful, venture.

Finally, the government's role as project initiator and manager drew the FAA far from its area of expertise. The SST project was the first time the U. S. government attempted to establish design specifications for a new commercial aircraft. Although the FAA had been responsible for certifying new aircraft designs as safe, this role had not prepared it to make the myriad trade-offs among various performance, weight, size, cost, and timing factors involved in designing commercial aircraft. FAA design competitions generated substantial controversy, and the aircraft's design was debated throughout the project's duration. This experience suggests the extreme difficulty government agencies face when they must substitute their discretion for that of private firms in the development of commercial technologies. Just as the familiarity of U.S. manufacturers with the requirements of their customers promoted U.S. success in early commercial aircraft development, the FAA's inexperience in commercial aircraft design curtailed its effectiveness.

2. Nuclear Power

Unlike the civilian aircraft industry, the development of commercial nuclear power relied heavily on direct and indirect government financial support. The bulk of this support came via the Atomic Energy Commission's (AEC) Power Reactor Demonstration Program (PRDP), which operated from 1955 until 1963, and through implicit insurance subsidies provided by the 1957 Price-Anderson Act.[40] Government activity in this area was motivated by mixed objectives, chiefly the rapid development of civilian nuclear power reactors to further national prestige and foreign policy goals. Other important objectives included promoting early development of "competitive" nuclear systems, and obtaining private sector participation and funding for nuclear R&D.

Case studies of the evolution of nuclear power highlight two major points. First, substantial conflicts emerged among the government's various objectives; in particular, technology developed to meet the objective of being the first country to operate civilian nuclear-powered electric generating reactors was not necessarily compatible with the requirements of low-cost electricity. Second, the most substantial stumbling block to commercial development of nuclear power appears to have been its discouraging economics; throughout most of its early development, there was a broad consensus that nuclear power was not cost competitive with electricity from

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[40] The Price-Anderson Act indemnified nuclear plant operators against liability in excess of the amount of coverage available at "reasonable" cost through commercial insurance markets. At the time of the Act's passage, this amount was set as $60 million. The Act also limited federal liability to a maximum of $500 million, a figure that has been held constant through 1986.

fossil fuels.[41] Appropriability concerns and disincentives arising from public utility regulation of electric utilities and government restrictions on private use of nuclear technology may have further reduced private sector interest. Capital market failure can be ruled out as an important factor. These issues are addressed in the analysis below.

A. Early Development of Nuclear Power. The development of nuclear reactors for electricity generation originated in the U.S. Navy's reactor development program after World War II. At the instigation of Captain Hyman Rickover, the Navy designed and constructed a reactor for use in its nuclear submarine demonstration project. Rickover selected the pressurized water reactor (PWR) technology, in the interests of reliability and rapid development. The first prototype PWR began successful operation in 1953.

The transfer of nuclear reactor technology to the civilian sector also was initiated in 1953, when newly-elected President Eisenhower decided that a strictly civilian nuclear reactor project was essential to U.S. prestige and foreign policy objectives.[42] The Administration's emphasis on being the first country to put a wholly civilian reactor on-line dictated retention of the PWR design developed by the Navy. Construction of the 60 MW Shippingport nuclear power plant, a joint project of the AEC, Westinghouse, and Duquesne Power and Light, was begun in late 1954. By this time, the PWR design was the most mature nuclear technology, although a number of other

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[41] There was disagreement, however, over expected future costs. Proponents of nuclear power believed that learning-by-doing and economies of scale would reduce these substantially.

[42] Eisenhower thought it imperative that the U.S. demonstrate a commitment to peaceful uses of atomic energy. This concern gave rise to his "Atoms for Peace" policy, and to such projects as the Nuclear Ship Savannah.

reactor technologies were being pursued, many of which were thought to hold more commercial promise.

Despite advances in nuclear reactor R&D and design during the early 1950s, the private sector appeared hesitant to invest in developing the new technology. This was attributed in large part to tight government restrictions on the use of nuclear fuels and technologies. Much of the government's technological information on nuclear energy was classified or closely held. Patent protection for advances in nuclear designs was restricted, and private ownership of nuclear fuels and facilities was prohibited. Congress responded to these concerns with the 1954 Atomic Energy Act, which greatly relaxed government restrictions and provided for AEC service and materials support to firms undertaking commercial development of nuclear power.[43]

Passage of the 1954 Atomic Energy Act had little immediate impact on stimulating private involvement in the development of nuclear power. While the earlier restrictions may have had some incremental effect in discouraging private investment in nuclear power, it appears that the uncertain economics of the technology overwhelmed most other considerations.[44] The role of possible non-appropriabilities in discouraging investment is more difficult to determine, particularly as contemporary accounts did not focus on this issue. Most proponents of nuclear power expected substantial cost reductions from learning-by-doing; if these were expected to accrue to the

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[43] The Act continued to prohibit private ownership of nuclear fuels, but did provide for private use of these fuels.

[44] See Perry et al. (1977), p. 19. Although some observers described this reluctance as risk aversion by utilities, it seems more likely that it was aversion to investing in unprofitable technologies. Even the more optimistic supporters of nuclear power suggested only that costs would decline to a level competitive with fossil fuels at some point in the future, not that nuclear costs were competitive in the immediate term.

industry as a whole, they may have contributed to the decision not to invest. While _expected_ industry-wide learning economies are difficult to discern, the _realized_ industry-wide learning economies for the early commercial plants do not appear to have been substantial.[45]

Whatever the causes, when the expected surge of interest in nuclear power failed to materialize after the 1954 Act, the AEC decided to pursue a more direct approach to encouraging private development of nuclear power. To this end, the Commission announced the initiation of its Power Reactor Demonstration Program in January 1955.

B. The Power Reactor Demonstration Program. The AEC's PRDP, which lasted from 1955 until 1963, was intended "to bring private resources into the development of engineering information on the performance of nuclear power reactors and to advance the time when nuclear power will become economically competitive."[46] The PRDP went through several rounds of proposals, each targeted at somewhat different technologies or groups of utilities and providing slightly different forms of financial assistance. The basic forms of AEC assistance included waivers of fuel use charges for the initial years of operation and R&D contracts to subsidize pre- and post-construction

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[45] Zimmerman (1982) finds that two-thirds of the learning economies in nuclear construction costs are firm-specific. He finds that roughly half the learning about costs is firm-specific information. Because of overly optimistic estimates of nuclear costs, however, the net effect of completing one commercial scale nuclear plant by 1965 would have been to _reduce_ the rate of commercialization.

[46] AEC Press Release, cited in Allen (1977), p. 39.

R&D.[47] As a condition of its assistance, however, the AEC typically insisted upon fixed cost contracts; utilities, suppliers, and contractors would bear all the risk associated with the projects. In addition AEC R&D contracts required that "information derived from operation under the contract be made available by the AEC...to the entire technical public working on reactor development..."[48]

The number of nuclear plants built under the PRDP is small, and the number of technologically successful ones still smaller. Of the three first round proposals that were funded, only Yankee, a 175 MW PWR, was successfully completed and operated.[49] The second round was directed at involving small publicly-owned utilities in the development of small, highly experimental reactors. Not surprisingly, the mismatch of immature technologies with a commercially-oriented demonstration program, and small, financially limited public utilities with high-risk experimental R&D projects was not particularly successful. Only two second round projects were completed; both were shut down within a few years of initial operation. An additional

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[47] Under the 1954 Atomic Energy Act, the AEC was prohibited from providing financial assistance for the construction of reactors used to generate electricity. It could, however, finance R&D on such reactors. AEC R&D assistance also was provided to equalize access to technological information across a broader range of utilities and manufactures.

[48] AEC Press Release No. 589, January 10, 1955.

[49] The other two projects that were accepted and funded by the AEC were the Fermi fast breeder reactor and the Hallam sodium graphite reactor. Both were plagued by delays and multiple technological problems.

Two additional reactors were begun at this time without AEC R&D assistance. The 200 MW Dresden boiling water reactor (BWR) was initially proposed as a first round project, by a consortium of utilities headed by Commonwealth Edison. The group ultimately waived its request for AEC assistance, and began construction of the privately-financed reactor in 1955. The 265 MW Indian Point PWR, financed by Consolidated Edison, also was begun in 1955. Both of these reactors are viewed as successful.

eight plants were begun between 1957 and 1962; four as part of the formal third round and modified third round projects, and four that were not formally part of the demonstration program, but which received AEC assistance on terms similar to those of second and third round projects. The results of these were mixed. In general, the more mature reactor technologies were more successfully implemented; those that used experimental designs tended to demonstrate only "that some particular species of reactor was not quite ready for demonstration."[50]

The first commercially-scaled nuclear power plants to be constructed--the 375 MW San Onofre PWR and the 490 MW Connecticut Yankee PWR--also were the last two plants to be built under the PRDP.[51] Construction on these plants began in 1962, only two years after the initial operation of Yankee. In 1963, well before any large scale nuclear plants were operational, the AEC decided that the light water technologies represented by pressurized water reactors and boiling water reactors had achieved commercial viability, and terminated the PRDP.

Although promoted as a program to demonstrate the technological and commercial feasibility of nuclear power, the AEC used the PRDP to further a multiplicity of goals. Objectives pursued in soliciting and evaluating proposals included increasing the number of manufacturers involved in nuclear reactor development, expanding utility participation to include small publicly owned utilities as well as large investor owned firms,

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[50] Perry et al. (1977), p. 14.

[51] These are included among the eight third round and modified third round plants described above.

extending the scope of R&D on new and experimental nuclear technologies at minimum cost to the AEC, as well as hastening commercial development of nuclear power. These objectives were not mutually consistent, and the attempt to include them all within a commercial demonstration program created a number of problems.

First, by confusing R&D objectives with demonstration of the technical or commercial feasibility of known technologies, the AEC reduced the ability of the program to meet either goal. Potentially promising but highly experimental technologies may have been discarded when they failed to meet the standards of a demonstration program--even though those standards are inappropriate for immature research designs. The commitment to an early demonstration program may have pushed a commercially inferior, but technologically more mature design into the forefront. At the initiation of the PRDP in 1955, the technology most suitable for near-term demonstration was the pressurized water reactor design. Of the five reactor technologies then under consideration by the AEC, however, the PWR design was thought to be the least promising from a long-run commercial standpoint.[52] Its establishment as the commercial technology of choice may have been due primarily to the PRDP's focus on rapid commercialization.

Second, the Commission's emphasis on accelerating the commercialization of nuclear power may have been quite costly. In addition to possible distortion of technology choice, the PRDP may have reduced gains from learning-by-doing. The early rounds of the PRDP were compressed so closely together that very little learning could be transferred from one stage to

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[52] See Allen (1977), pp. 155-156. The other technologies were: sodium graphite, boiling water, homogeneous, and fast breeder.

the next. Construction of Yankee was begun before Shippingport was operational; second round proposals were solicited before the AEC could evaluate any first round experience; third round proposals were solicited before any first round plants were operational; and commercial scale-ups of PWR designs were begun with only to two years of operating experience with Yankee and Consolidated Edison's privately financed Indian Point PWR. Zimmerman's (1982) study of learning effects in commercial-scale nuclear plant construction suggests that potential learning economies were significant. For example, experience gained from completion of the first commercial-scale plant was estimated to reduce future plant construction costs by roughly 12 percent. As one-third of those cost savings accrue only as the plant nears completion, overlapping construction phases limits available savings.[53]

Third, the emphasis on rapid development also may have reduced the industry's ability to incorporate learning about potential safety problems into the next generation of plant designs, necessitating expensive redesigns and retrofits once safety concerns emerged from early plant operations. This was compounded by the Price-Anderson Act, which reduced the industry's incentives to invest in safety R&D by subsidizing the cost of liability insurance.

Finally, the AEC's objective of increasing manufacturer and utility participation conflicted with the Commission's insistence on limiting AEC financial exposure, and was hampered by electric utility rate regulation. The AEC's financial assistance typically amounted to 10 to 20 percent of

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[53] Zimmerman finds that industry-wide learning economies are a function of completed plants rather than reactor-years of construction, suggesting that dissemination of technological information occurs at the end of the construction period.

total cost for first and third round projects, and the Commission's fixed dollar contribution did little to reduce the risks or uncertainties faced by investors. This curtailed the ability of smaller utilities and manufacturers to participate, although the AEC encouraged such participation, particularly in the unsuccessful second round. Utility participation may have been further discouraged by the structure of electric utility regulation, which effectively increased utilities' risk aversion as investors in new technologies. Rate regulation can distort decisions by forcing utilities to bear all of the costs of risky investments, but allowing them only a portion of the benefits of any successful investments.[54] This will reduce the attractiveness of riskier investments to utility shareholders, and enhance the importance of diversification schemes. In line with this, almost all of the early nuclear power projects were undertaken by large consortia of utilities.[55] The use of consortia minimized an individual firm's risk exposure, and permitted diversification of risk across broad segments of the industry.

Utility leadership was not critical to commercial development of nuclear power, however. Manufacturers of electrical generating equipment,--General Electric and Westinghouse, in particular--had acquired extensive

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[54] Many state regulatory commissions prohibited recovery of R&D outlays through electricity rates. If investments in nuclear power were unsuccessful, utility shareholders would bear the entire cost. If nuclear power turned out to be commercially successful, however, regulators were almost certain to flow the cost savings through to consumers. Because regulation essentially limits utilities to a "fair rate of return" on capital investments, utility profits were capped at the level earned by low-risk, conventional investments.

[55] The primary exceptions were second round projects, which relied on substantial federal financing (in the range of 70 to 90 percent) and typically were built by individual publicly owned utilities.

nuclear experience through their government contracts and participation in the PRDP. These firms had substantial capital resources, and were capable of financing considerable investments in new technology. These factors made them natural candidates for private sector development of nuclear power. The AEC's success in promoting the commercial development of nuclear power may have been a result of convincing the large manufacturers, rather than the utility industry, of the commercial viability of nuclear power.

C. Early Commercialization of Nuclear Power. The commercial growth of nuclear power relied substantially on the willingness of manufacturers to take on the risks associated with building large-scale nuclear power plants. After Westinghouse captured both the Connecticut Yankee and San Onofre contracts, GE decided that it had to do something dramatic if it wanted to remain in the nuclear reactor business. In 1963 GE reached a contract agreement with Jersey Central Power and Light for construction of Oyster Creek I, a 640 MW boiling water reactor. The agreement, described as a "turnkey" contract, was innovative. For a fixed price of $66 million, GE accepted responsibility for everything from plant design to permitting, construction, and licensing; the utility would simply "turn the key" to begin operation. The contract price was similarly innovative, set to yield electric power at a cost slightly below the cost of electricity from new fossil-fuel units. Although the plant was expected to cost considerably more than $66 million to build, GE expected substantial learning economies, and hoped to recoup some of the initial design costs on future orders.

Oyster Creek marked a turning point in the commercialization of nuclear power. The Oyster Creek contract convinced the AEC that nuclear power had achieved commercial viability, and prompted the Commission to announce the termination of its demonstration program.[56] The AEC's judgment was corroborated by a flurry of commercial orders for nuclear plants in the wake of Oyster Creek I: between 1963 and 1967, GE agreed to construct seven turnkey BWR plants, Westinghouse signed turnkey contracts for six PWR plants, and utilities ordered 27 non-turnkey plants.[57]

The AEC's PRDP was instrumental in sparking this development. The Oyster Creek contract was a direct response to Westinghouse's success in capturing the San Onofre and Connecticut Yankee contracts under the PRDP, and to GE's fear that it would be closed out of the nuclear plant market. Had the PRDP not accelerated the introduction of large-scale nuclear plants, commercial development would probably have been delayed. It is unclear, however, that this accomplishment was desirable from an economic standpoint.

The expected scale and learning economies built into turnkey prices were wildly optimistic, and expected nuclear plant costs were substantially understated. GE and Westinghouse lost an estimated $875 million to $1.0 billion on their 13 turnkey plants, for which actual construction costs were roughly double the price charged to utilities. The ability of GE and Westinghouse to finance these losses suggests that capital market failures

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[56] This shifted the AEC's attention to the development of breeder reactors, and led to the eventual creation of the Clinch River Liquid Metal Fast Breeder Reactor project. Although not discussed in detail in this paper, the Clinch River project history bears a striking resemblance to that of the SST. The Clinch River Project, which was the target of years of criticism, had escalated from an initial cost estimate of $500 million to outlays of $1.5 billion on total estimated costs of $3 billion before the project's termination in 1983. See Young (1984) for a favorable discussion of the project.

[57] Following convention, this accounting includes the San Onofre contract among Westinghouse's turnkey plants. See Perry et al. (1977), pp. 28-33, 38.

were not responsible for early reluctance to construct privately-financed nuclear plants. The magnitude of the losses also suggests that the initial doubts about the economic potential of nuclear power were probably right. Nuclear power was far from cost competitive with electricity from fossil fuel in most areas, until the OPEC embargo and oil price shock in 1973-74.

Ex ante, not ex post, costs should be used to judge the economics of an investment, so the fact that realized costs exceeded expectations is not itself an indictment of early investments in nuclear power. Had the pace of commercialization been slower, however, the costs of investments in nuclear power might have been reduced. In particular, delaying commercial orders might have allowed utilities to take advantage of learning about the true costs of nuclear plants, and reduced potentially uneconomic investment in nuclear power. To this extent, the government's acceleration of nuclear power may have increased electricity costs.

3. Communications Satellites[58]

The communications satellite industry exemplifies a third style of federal intervention in technology development. As with nuclear power, initial government research on satellites was concentrated in the Department of Defense and focused on military applications. Government-sponsored R&D on civilian satellites was not begun until the creation of the National Aeronautics and Space Administration (NASA) in 1958. Unlike nuclear power, however, there was strong private interest in satellite technology from a very early stage of its development. Private research efforts, which predated NASA, exerted considerable influence on the direction and pace of the government's civilian R&D program. Moreover, in contrast to both the commercial aircraft and nuclear power industries, the federal government actively restrained early attempts to commercialize communications satellites. Restraints were imposed both by congressional action culminating in the Communications Satellite Act of 1962 and by the pre-existing system of communications regulation administered by the Federal Communications Commission (FCC).

These policies were motivated by two dominant concerns. First, political goals were quite influential: national prestige had been badly bruised by Russia's Sputnik launch, and the U. S. was searching for a space technology in which it could demonstrate preeminence. Development of communications satellite technology was NASA's first major project in this effort. Second, there was considerable fear that AT&T would use the new technology to extend its domestic telecommunications monopoly. Concern over AT&T's market dominance shaped much of the government's commercialization policy.

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[58] The material in this section is drawn primarily from Smith (1976).

A. Early Satellite Development. NASA's early satellite research, under the Echo project, focused exclusively on passive satellites.[59] By the inception of Echo in 1958, however, private industry was shifting its interest toward the development of active repeater satellites, which were believed to have numerous advantages over passive satellites, and to be within technical reach.[60] NASA initially resisted the escalating private pressure for development of active communication satellite systems. Not until late 1960 did the agency's position change. The new policy was in part a response to extensive "lobbying" by private firms, especially AT&T and Hughes, which were designing active satellite systems.[61]

As part of its new initiative, NASA opened competitive bidding for government-sponsored development of an active repeater satellite in late 1960. Seven bids, including AT&T's, were received. NASA rejected AT&T's proposal in favor of RCA's Relay satellite, although NASA agreed in July

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[59] Passive satellites, which essentially act as radio "mirrors," are quite simple, but require powerful and sophisticated ground stations. Active satellites, which receive and re-transmit signals, require less powerful ground stations, but more sophisticated electronics aboard the satellite. A 1958 NASA and Department of Defense (DoD) agreement gave NASA R&D responsibility for passive satellites, DoD R&D responsibility for active satellites.

[60] These include lower cost ground stations and better control of satellite use. In addition, because active satellites amplify and re-transmit signals, they are suitable for higher orbits. Orbit height increases both the amount of territory in view of the satellite and the amount of time a satellite is in view of a given earth station, reducing the number of satellites necessary to maintain continuous communications worldwide.

[61] For example, AT&T had proposed a system of 50 low-orbit active repeater satellites to the FCC, and asked NASA to provide launch services on a reimbursable basis. Within two weeks of NASA policy announcement in October, AT&T announced that it was prepared to commit $30 million to the development of an active repeater satellite, and up to three times that amount if the project proved feasible.

1961 to provide launch support for AT&T's Telstar satellite.[62] NASA also signed a sole source contract with Hughes in August 1961, to develop an innovative geosynchronous satellite design under the Syncom project.[63] The Hughes design was the most advanced, and the most risky, of the three NASA projects.

The first Relay and Telstar launches took place in 1962; Syncom followed a year later. Although all three experiments were successful, Syncom was the most rewarding. Prior to Syncom, geosynchronous satellites were thought to be a distant possibility requiring extensive R&D to bring to fruition.[64] The Syncom project was so successful that plans for a commercial system of medium-altitude satellites based on AT&T's Telstar were scrapped in 1963. The first U. S. commercial satellite launch, Early Bird in 1965, was a geosynchronous satellite. These are the mainstay of the international telecommunications system today.

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[62] Under the terms of the agreement, AT&T would develop the satellite and reimburse NASA for the cost of launch facilities and services. NASA would provide launch vehicles and tracking services. AT&T agreed to release to NASA the results of its experiments and the rights to use any patentable inventions produced during the project.

[63] The design was one Hughes had worked on internally. Unlike AT&T, Hughes appeared unwilling to develop the satellite with private capital.

Geosynchronous satellites, located in high earth orbit 22,300 miles above the equator, have an orbit that exactly matches the rotation of the earth, and therefore appear as stationary from the standpoint of a given ground station. More powerful rockets are required to launch to geosynchronous orbit, but tracking facilities are greatly simplified and the number of satellites needed for an international communication system is substantially reduced. They provide considerable advantages over low-orbit satellites.

[64] The only existing geosynchronous project, the Advent satellite being developed by DoD, had run into substantial difficulties; it was cancelled in 1962.

The government's involvement in developing and demonstrating communication satellite technologies does not appear to have been motivated by the economic rationales discussed in section I. Although some official reports expressed doubt about the ability of the private sector to finance development of communications satellite technology,[65] capital market failure arguments are rather unpersuasive in light of AT&T's privately-financed Telstar project. Unclear regulatory jurisdictions and FCC spectrum regulation appear to have contributed to the delay of commercial satellite systems, but do not seem to have inspired government support of satellite R&D. Nor does non-appropriability of research results appear to have been a substantial factor, at least for AT&T. Because of the company's dominant position in the telecommunications industry, it would have been able to internalize most of the benefits from its communications satellite research.[66]

The primary motivation for government intervention appears to have been perceived economic and political threats from AT&T's eagerness to develop a private satellite system. From an economic standpoint, the government was reluctant to allow AT&T to take the lead in a situation that might enable it to leverage its domestic telecommunications monopoly into an international monopoly on satellite communications. Monopoly may be associated with

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[65] President-elect Kennedy's Ad Hoc Committee on Space, headed by Jerome Weisner, argued that "the development investment required is so large that it is beyond the financial resources of even our largest private industry." Cited in Smith (1976), p. 77.

[66] Hughes' reluctance to invest in development of its synchronous satellite may have been partially due to expected non-appropriability. Hughes may have been doubtful of its ability to sell its synchronous satellite, given AT&T's position as both a competitor in satellite development and the dominant customer for satellite services. This problem arises because of AT&T's monopoly position; I therefore class it as a monopoly problem, rather than non-appropriability *per se*.

myriad market inefficiencies, including excessively high prices and restriction of output, distorted R&D incentives, self-dealing (e. g., purchasing equipment only from subsidiaries, to extend the monopoly upstream in the production process), and possibly inefficient use of new technologies. Government-sponsored R&D was used to provide an alternative to AT&T, in an effort to keep the satellite field open to more than one firm. Political issues also were important. For example, NASA's decision to request proposals for satellite development, and possibly its rejection of AT&T's initial bid, appears at least in part to have been motivated by concern that AT&T not overshadow NASA's research program.[67]

B. COMSAT. While NASA was engaged in R&D on satellite technology, Congress debated the role of public versus private ownership of communications satellite systems. Three alternatives were considered: private ownership by the international telecommunications carriers (AT&T, ITT, RCA, and Western Union), broad-based private ownership with limits on ownership shares of the telecommunications carriers, and government ownership.[68] The debate focused primarily on the issue of monopoly. There was widespread resistance to allowing the international carriers to own and operate the satellite communications system:

> The possibility would always exist that such ownership would result in limiting competition among the carriers in the furnishing of communication services, in the manufacture and sale of communication equipment, or in

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[67] See Smith (1976), p. 70ff.

[68] These were embodied in three Senate bills: the Kerr bill (supported by the FCC), the Administration's bill, and the Kefauver bill, respectively.

> limiting competition in either of these areas of non-participating companies. Furthermore such limited ownership might well give de facto control to a single company, AT&T.[69]

There was considerable concern that even a scheme of broad-based private ownership with government regulation of operations would provide insufficient checks on any monopolistic tendencies. This concern, along with the view that the private sector should not be permitted to profit from technology developed at government expense, gave strength to proposals for government ownership.

The Communications Satellite Act of 1962 represented a distinctive compromise among these positions. The act created COMSAT as a unique public/ private organization. COMSAT was established as a private corporation, and given a U. S. monopoly on intercontinental satellite communications. In exchange, the government created an elaborate system of checks on possible abuse of that monopoly. Ownership in COMSAT was to be broad-based, and the international telecommunications carriers' joint ownership share was limited to no more than 50 percent at all times. COMSAT was to be financed initially through a public stock offering, with 50 percent of the shares reserved for the carriers. Additional capital could be provided by the carriers through future issues of non-voting stock. The FCC and other government entities were given extensive regulatory authority over COMSAT operations.[70] Finally, in an almost unprecedented move, Congress

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[69] Assistant Attorney General Lee Loevinger, testifying before the Senate Judiciary Committee in 1962. Cited in Smith (1976), p. 98.

[70] The President, NASA, the State Department, and the FCC were given prescribed oversight roles. The FCC's range of control was the broadest; it ranged from enforcement of the act's competitive bidding and non-discriminatory access clauses, to rate-making and regulation of capital and

provided for government appointment of three of the eighteen members of COMSAT's Board of Directors.[71]

Although approved in 1962, COMSAT faced a number of delays before becoming operational. This was in part a result of the various layers of governmental action required by the 1962 Act, and perhaps in part a result of strategic delay by the corporation.[72] The lag was in some ways beneficial to the development of COMSAT's commercial system. The corporation began issuing stock in 1964, based on a $200 million capital requirement for a medium-altitude satellite system. By the end of 1964, however, NASA's results from the Syncom project were so encouraging that COMSAT was able to switch to a much lower cost geosynchronous satellite system. If system construction had begun earlier, this option would not have been as easily exercised.

The creation of COMSAT did not resolve, and perhaps exacerbated, one persistent conflict: how to define the appropriate role for government R&D. Once COMSAT was established, many congressmen expected the private sector to take over the bulk of satellite development. Despite this, the NASA budget for satellite communications actually expanded during the years immediately following COMSAT's creation. Although NASA shifted its research program

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financing decisions, to approval of technical specifications for satellite systems.

[71] Congress had made a similar provision when it created the Union Pacific Railroad in 1863. However, the government had a financial interest in the Union Pacific; it had none in COMSAT. Smith (1976), p. 107.

[72] COMSAT was accused by some of delaying its stock issue as a means of postponing operation, to take advantage of further NASA R&D expenditures.

away from areas of private interest once those areas were clearly identified, the delineation between private and public research has proved especially difficult to determine.

Advocates of NASA's broad applications research agenda point to the lack of interest by the private sector in developing particular technologies such as geosynchronous satellites, although it is difficult to assess what private investments would have been made in the absence of NASA programs. For example, NASA's sponsorship of Hughes' Syncom design had a tremendous impact on the industry. Whereas AT&T and others had assumed that geosynchronous satellite technology was quite distant, NASA was able to develop the technology to the point of demonstrating commercial feasibility within three years. On the other hand, it is unclear what would have happened to Hughes' design had NASA not been engaged in satellite R&D. Hughes' reluctance to finance the project internally may have been in part a response to the belief that government funds would be available. NASA's subsequent research on advanced satellite technology and applications raises similar questions. It seems inconceivable that NASA does not crowd out some private investment, but there are no definitive conclusions as to the significance of this effect.

The development of the communications satellite industry also highlights the complications that can be induced by various policies and regulations that pre-date development of a new technology. AT&T's satellite research involved the company in countless consultations with NASA, the FCC, and international agencies, and required numerous applications for various types of authority. Uncertainty over regulatory policy also created substantial delays in the introduction of satellite systems. For example, eight years elapsed between the first application to the FCC for domestic satellite authority in 1965, and the Commission's first construction authorization in 1973. The intervening years were spent in a confusing sequence of policy proposals, revisions, announcements, and retractions, as the FCC struggled to decide what guidelines to follow in approving domestic satellite systems. By the time the situation was resolved, roughly half of the prospective domestic satellite operators had withdrawn from consideration.

Regulatory policy has also affected technology choice and the direction of R&D on communications satellites. The operation of communications satellites requires inputs of two "common pool" resources: a frequency allocation, or portion of the broadcast spectrum, and a location in geostationary orbit, or orbital "slot." Both of these are international resources, for which private ownership rights have historically been rejected. Assignment of slots and frequencies to U. S. satellite operators is the responsibility of the FCC. The Commission has historically decided these assignments by regulatory review of applications, much as it decides entry applications in radio and television broadcasting. By failing to allocate resources to the highest value users, and by setting an implicit price for these resources near zero, these regulatory mechanisms tend to increase the effective scarcity of slots and frequency allocations. This has distorted technology choice and R&D toward hardware-intensive satellites that minimize orbital requirements.[73] Rather than compensating for this distortion, however, NASA's government-sponsored research has generally reinforced this bias.

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[73] See Macauley (1986).

III. Guidelines for Commercialization Policy

A number of common themes emerge from the case studies of technology development analyzed in section II. These are not unique to the particular set of industries selected for my analysis, but apply across a broad range of technologies.[74] This section draws upon these themes, referencing both the case studies in section II and analyses of other technologies, to develop broad guidelines for the government's space commercialization policy. The intent of this section is to signpost general directions. Defining specific policies toward particular technologies would require detailed analysis that is beyond the scope of the paper.

1. Don't push commercialization.

The histories of technology development speak most eloquently on this issue. Government policies to stimulate more rapid commercialization of a technology typically are quite costly relative to their accomplishments, and frequently are counter-productive to their objective. A number of lessons emerge from the case studies. First, the case studies strongly reject capital market rationales for government intervention in the commercialization of technologies. The private sector has clearly demonstrated its ability and willingness to finance a broad range of technology development in the industries reviewed. Commercial aircraft from the Ford Trimotor through the Boeing 767, commercial-scale nuclear power plants, and much of the early communications satellite R&D were financed privately.

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[74] See, for example, discussions and references in Ahearne (1985), Baer et al. (1976), Eads and Nelson (1971), Joskow and Pindyck (1979), Nelson (1982, 1984), Nelson and Langlois (1983), and Schmalensee (1980).

Private sector reluctance to provide capital for commercial development appears to have been a fairly strong signal of the project's discouraging economics, rather than a signal of market failure. Commercial projects that are developed only with substantial government financial support frequently fail to develop into viable enterprises. The SST, Clinch River breeder reactor, and a variety of Synfuels projects stand out in this regard, although they are not unique.[75] For example, a study of 24 federally funded demonstration projects across a wide range of industries found that private initiation of projects and the extent of nonfederal cost-sharing were closely linked to the project's diffusion success.[76] Apparently, the willingness of the private sector to provide substantial funding for certain projects reflected these projects' greater potential for commercial success. These experiences suggest that the government should make more use of capital market assessments in designing policy. An assumption that the capital market is prima facie efficient in allocating capital to new ventures seems an appropriate policy guide, absent clearly identifiable non-appropriabilities or other distortions.

Second, the case studies suggest that accelerating technology development may be counter-productive to commercialization goals. Although being first with a new technology may yield political dividends, it is not a clearly dominant commercial strategy. For example, U. S. aircraft manufacturers in the 1920s and 1930s benefitted tremendously from earlier European, particularly German, theoretical studies and designs. Britain's early

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[75] See, for example, summaries provided by Nelson and Langlois (1983), and Baer, Johnson, and Merrow (1977).

[76] See Baer et al. (1976) and Baer, Johnson, and Merrow (1977).

development of the Comet jet airliner did not confer substantial advantages on de Havilland. Instead, U. S. manufacturers may have realized significant "second mover" advantages, by beginning production with larger, more efficient planes, and by learning from the Comets' disastrous experience with structural fatigue in pressurized cabin designs. The SST/Concorde experience reinforces this message: being first may result in more publicity, but it can be quite costly. Perhaps the strongest example of potential second mover advantages is the country of Japan, which has done extremely well in high-technology commercial enterprise, even though it rarely has been at the forefront of technology invention and innovation.

In addition, project costs tend to increase substantially as development speed rises, and technology choices may be constrained away from the optimal technology by an emphasis on rapid development. The reliance on light water reactors for nuclear power, and the early dismissal of a number of experimental technologies, was strongly influenced by the AEC's objective of stimulating faster development. If commercialization of communications satellite systems had been accelerated rather than restrained, a substantial investment might have been made in low- or medium-altitude satellites and their associated ground stations and tracking facilities--only to become obsolete immediately afterward.

Finally, even if a strong argument could be made for developing a commercial technology that the private sector has passed up, the government's track record suggests the desirability of self-restraint. Government direction of technologies for commercial use, as opposed to government use, frequently fails. This is aptly illustrated by the SST project in the U. S., and by the British and European experience in aircraft development more generally.[77] Government agencies typically are poorly equipped to manage development of commercial technologies, and transferring projects to the government increases the likelihood that political expediencies will override economic objectives. This is particularly true for large-scale projects, which seem to attract more political attention because of their budget visibility.[78]

The formulation of space commercialization policies could benefit from the lessons of these earlier commercialization efforts. They suggest, for example, that the government's program to commercialize the LANDSAT/ remote sensing satellite system may be misguided and premature.[79] They also suggest caution in evaluating arguments for NASA subsidies that rely on the inability of the private sector to finance development of such technologies as materials processing in space.

2. Target financial support at basic R&D or generic research.

A second theme of the case studies analyzed in this paper, and of technologies studied elsewhere, is the potentially high payoff to government-sponsored basic or generic R&D. Non-appropriability problems may be particularly severe for basic research investments, leading private industry

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[77] See Eads and Nelson (1971). Even Airbus Industries, which is one of the few European aircraft ventures that have achieved a degree of success as measured by sales, is hardly a successful venture by commercial standards. Sales are quite unlikely to return the participating governments' investments of roughly $2.5 billion in Airbus subsidies. See Krugman (1984).

[78] See the discussion in Ahearne (1985), pp. 18-24.

[79] Commercial development of this system is also hampered by the public good nature of much of its output. Because of difficulties appropriating the benefits of public goods, the private sector will tend to undersupply them.

to invest too little. Generic research, which refers to early stages of applied research that have a wide scope of applications not all of which are necessarily commercial, is another candidate for government investment.

These interventions are most suitable for infant technologies. For example, during the early development of the commercial aircraft industry, NACA research and testing had a broad range of both commercial and military applications. As the technology matured, spillovers between military and commercial applications declined--reducing both the effectiveness of generic research and the rationale for government sponsorship. Government-sponsored research on various experimental reactor designs during the early stages of nuclear reactor development could be justified by both technology spillovers and the difficulty of appropriating cost information. Once the feasibility of pressurized water reactor and boiling water reactor designs had been demonstrated in early pilot plants, however, design refinements and commercial scale-ups did not seem to involve substantial non-appropriabilities. NASA sponsorship of Hughes' geosynchronous satellite experiment also yielded high benefits, as geosynchronous satellite designs were adopted for both international and (subsequently) domestic satellite systems. However, given the market structure of the communications satellite industry, one would not expect non-appropriabilities to deter private investment in applications R&D.

The histories also illustrate the difficulty of deciding when government-sponsored research should stop and private research should begin. In particular, there is a tendency to continue government sponsorship well past the basic or applied research stage--despite the fact that the non-appropriability rationale used to justify the initial intervention may no longer apply. The Atomic Energy Commission's Power Reactor Demonstration Program extended government financial support to nuclear power plants past the R&D stage and into the commercialization phase of technology development. NASA's satellite research program appears to have been particularly susceptible to this tendency. The agency has had a strong bias throughout its history of pursuing technology development well into the applications phase. While this may be in accord with NASA's mission in scientific endeavors, providing financial support up to the operational stage of development for most potential commercial technologies does not appear justified on the basis of non-appropriability of benefits.

When the government finances technology development past the stage justified by non-appropriabilities, one of three things tends to happen. Either (1) government funding simply replaces private funding, creating pure wealth transfers to the industry in question; or (2) government funding increases the total resources devoted to technology development, resulting in excessive investment in the industry relative to the socially optimal level; or (3) government funding reduces the costs of developing particular technologies and distorts the ultimate technology choice.

This suggests the need to re-think current policy directions in such areas as materials processing in space. Experience with other technologies suggests that the economic rationale for government subsidies to MPS diminishes sharply as the technologies mature. Proposals to continue government subsidies past the early experimental stages, such as policies to provide free or low-cost transportation for MPS projects until the first revenue-producing flight, should be viewed with skepticism. Those advocating such policies should be given the burden of proof in justifying such support.

3. Some types of government intervention may make things worse.

The case studies suggest that the form of the government's intervention in technology development is as important as the decision to intervene itself. If the government does decide to promote the development of a commercial technology, it must carefully structure its policies to account for possible interactions with pre-existing government distortions or other market failures, and to minimize potential adverse incentives. These tasks, while far from simple, are required to mitigate unexpected consequences of the policy intervention.

For example, the Price-Anderson Act of 1957 limited utilities' liability for nuclear accidents. The Act appears to have been enacted, at least in part, on the belief that some implicit insurance industry failure was responsible for utilities' inability to obtain "sufficient" liability insurance at a "reasonable" premium. While it may have achieved its primary goal of encouraging utility investment in nuclear power, it also reduced incentives for utilities to invest in safety research on nuclear power, and it may have discouraged investment in other electric generating technologies by implicitly subsidizing nuclear power.

The studies also suggest that it is not sufficient to require private cost-sharing in commercial development projects; there must be some risk-sharing as well, if incentives for efficient development are to be maintained. The SST and Clinch River projects highlight this point. For example, the utility industry contributed roughly half of the estimated $500 million cost of the breeder reactor at the beginning of the project. However, no additional utility contributions were required, even as project costs escalated toward $3 billion. By fixing the private sector contribution, the government eliminated incentives for utilities either to monitor the project's costs or to halt the project when those costs greatly exceeded the potential benefits of completing the reactor.

Failure to account for interactions with existing government regulations may lead to compounding distortions. For example, CAB regulation of the airline industry appears to have encouraged excessive investment in new aircraft. Had the U. S. government decided to promote the development of commercial jet airliners--as was suggested by a number of congressmen at the time--the incentive for excessive investment in commercial aircraft would have worsened, not improved, the efficient development of the commercial aircraft industry. Distortions in technology choice, and the direction of R&D, were also noted in the interaction of FCC broadcast regulation and orbital allocations in the communications satellite industry.

If the government decides to promote the development of space technologies, the case studies suggest that careful attention should be given to how this is done. If, for example, the government decides that a privately-operated ELV fleet is important to national security, but not commercially viable in the absence of government support, then that support should be structured to minimize unwanted distortions. Raising shuttle prices or eliminating commercial cargo from the Shuttle manifest is unlikely to accomplish this objective. These policies would reduce the use of space transportation, discourage investment in activities that rely on space transportation, such as satellites and MPS, and shift commercial cargo to foreign ELV providers. An alternative policy, such as a flat rate subsidy per ELV launch, might avoid many of these distortion while promoting a private ELV industry. In this vein, output subsidies or purchase guarantees may be the most effective way to promote development of new products or services. The provide incentives for firms to develop new technologies, without directly specifying the form that technology should take.

4. Don't confuse political goals with commercialization policies.

The final theme that emerges from the studies of technology development is the tendency to confound the pursuit of political objectives with the development of commercial industries. A variety of political motivations are often prominent in the government's decision to promote technology development. For example, national leadership and prestige were important in the decision to promote nuclear power in the 1950s; these along with international competitiveness were major factors in the government's support of the SST program during the 1960s. National security objectives motivate the development of advanced weapons systems and military technologies; the Apollo space program was created to demonstrate U. S. technological pre-eminence in space. Although these goals may be good reasons to develop a technology, it is critical to recognize that their pursuit may not be compatible with developing a commercial technology.

The distinction between engineering success and economic success is the essential issue. Engineering success is evaluated by whether or not a particular technology works. For most of the non-commercial technologies, political objectives are satisfied by engineering success; that is, if the technology is operable. The Apollo program achieved its objective of placing a man on the moon, and was a major success; it was not evaluated against a yardstick of return on investment or cost per mile, but on whether or not we could land men on the moon and bring them back.

Such engineering successes are a necessary, but by no means sufficient, condition for economic success. Economic success requires not only that the technology work, but also that the product or service it provides is profitable.[80] To make development of a technology economically worthwhile, it is not enough that it can be developed; someone must be willing to pay enough for the services produced by the technology to cover the development costs. Thus, although the Concorde may represent a tremendous engineering success, it is not an economic success; its costs are too high to make it a commercially viable project.

Perhaps the most important lesson from the rich histories of technology development is that the government's frequent success in mobilizing resources to make major technological advances does not imply an aptitude for the development of commercially successful technologies. Technology may be forced, but economically successful technologies are more elusive. History suggests the wisdom of exercising restraint in government commercialization policies.

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[80] Strictly speaking, economic efficiency dictates development of technologies for which the social benefits exceed social costs. This calculus would include the value of benefits such as national prestige. If the government were rational, all projects undertaken would then satisfy this criteria. My discussion focuses on commercial projects, which I take to be projects that the private sector undertakes. Because of this, it seems reasonable to restrict the discussion to private costs and benefits, and hence, to frame the analysis in terms of profitability rather than net social welfare.

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