

## KNOW-HOW AND ASSET COMPLEMENTARITY AND DYNAMIC CAPABILITY ACCUMULATION: THE CASE OF R&D

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*Dynamic capabilities enable firms to create new products and processes and respond to changing market conditions. This empirical investigation of dynamic R&D capabilities deals with the role of complementary know-how and other assets in the context of changing conditions in the U.S. petroleum industry during the 1970s and early 1980s. The analysis suggests that, in response to rising oil prices, firms with larger amounts of complementary technological knowledge and physical assets also undertook larger amounts of R&D on coal conversion (a synthetic fuels process). © 1997 by John Wiley & Sons, Ltd.*

When firms seek to alter their stock of knowledge in response to change in the external environment, do such efforts depend on the firms' existing stocks of complementary know-how and other assets, and if so, how?<sup>1</sup> An empirical investigation of research and development (R&D) activity in the U.S. petroleum industry during the mid-1970s through the early 1980s provides one answer to this question. During the period examined here, the industry experienced two large and exogenous oil price increases. The firms responded in many ways, including by increasing R&D on synthetic fuels, with particular emphasis on coal gasification/liquefaction (also termed coal conversion). This study suggests that firms' accumulation of new coal gasification/liquefaction knowledge via R&D depended on a variety of firm resources, including complementary assets in the form of knowledge accumulated through R&D in technologically related businesses, and in the

form of physical assets which commercialization of coal conversion processes would exploit.

Teece and Pisano define *dynamic capabilities* as 'the subset of the competences/capabilities which allow the firm to create new products and processes and respond to changing market circumstances' (1994: 541). In the oil industry, the high level of synthetic fuels R&D constituted a response to changing market prices, with which the firms aimed to create new products (substitutes for oil and gas products) and processes (to refine the inputs). Relatedly, Dierickx and Cool (1989) point out that firms must accumulate some assets such as technological expertise over time, for example by undertaking R&D, and that increments to asset stocks may depend on the level of complementary asset stocks within the firm. Thus, when oil companies sought to augment their stock of capabilities via coal gasification/liquefaction R&D, firms with complementary resources that they could leverage in performing the R&D or in commercializing the outcome might also have performed greater amounts of R&D.

One potentially useful resource for the accumulation of knowledge via R&D is preexisting know-how within the firm derived from technologically related R&D and operations. Such com-

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<sup>1</sup> The term 'complementary' is used here according to common English usage to mean 'serving to fill out or complete' (G. & C. Merriam Co., 1972). The analysis does not address issues in the new literature on 'complementarities' of organizational, technological, and strategic choices (Milgrom and Roberts, 1990).

plementary knowledge can produce economies of scope, which 'arise from inputs that are shared, or utilized jointly without complete congestion' (Willig, 1979: 346), and therefore reduce unit costs of production. Within the firm, economies of scope can derive from the use in different business applications of the firm's underlying expertise, as well as from direct transfer (or spillover) of knowledge between the firm's businesses (Gort, 1962; Penrose, 1959).

Scott and Pascoe (1987) have suggested that firms engage in 'purposive diversification in R&D,' in order to exploit technological complementarities among research activities; evidence from the FTC Line of Business data indicates that some firms' R&D activities involved technological complementarities.<sup>2</sup> Patel and Pavitt (1994) also found that within U.S. industrial sectors, most firms had patents clustered in technologically related fields.<sup>3</sup> Additionally, Teece (1980) showed that the pattern of oil company alternative fuels R&D and operations was consistent with economies of scope within the firm due to complementary knowledge. This study provides statistical evidence which lends further support to Teece's findings.

One study (Henderson and Cockburn, 1996) has provided direct evidence of economies of scope in R&D; the authors found a positive association between the number of patents produced by a pharmaceutical firm in one research area and both the number of each firm's patents

<sup>2</sup> Research on economies of scope in R&D within the firm has dealt with the topic primarily in the context of product-market diversification. Jovanovic (1993) has developed an equilibrium economic model wherein product diversification enables firms to capture spillovers within the firm of R&D knowledge related to multiple products, which produces economies of scope. Empirical studies by MacDonald (1985) and Montgomery and Hariharan (1991) showed that firms with high R&D intensities (R&D relative to sales) tended to diversify into industries with high R&D intensities. Similarly, Stewart, Harris and Carleton (1984) and Harrison *et al.* (1991) found that acquiring firms who diversified via merger sought target firms with similar R&D intensity patterns. Mitchell (1989) also found that the probability of an incumbent's entry into a new technical subfield was positively related to possession of other specialized related assets such as R&D. These matches suggest that R&D-intensive diversifying firms may have thought they could use their R&D expertise in other product markets, consistent with anticipated economies of scope.

<sup>3</sup> Narin, Noma, and Perry (1987) also found in the pharmaceutical industry that concentration of company patents within a few patent classes was positively correlated with increases in company profits and sales.

in technologically related R&D areas and the number of R&D areas pursued by the firm. The present study also examines firm R&D at a highly disaggregated level, focusing on R&D inputs (i.e., expenditures) rather than outputs. The study also differs from Henderson and Cockburn in that it deals with a particular technology in detail: by incorporating variables which represent each of several sorts of knowledge capital within the firm, the analysis can assess which sorts of potentially complementary knowledge had the greatest correlation with coal conversion R&D spending. Additionally, this study examines knowledge complementarity as one of several influences on dynamic knowledge accumulation in response to changing market conditions.<sup>4</sup>

This article proceeds as follows. The next two sections describe the empirical setting, discuss dynamic capability accumulation in the empirical context of the oil industry, and present testable hypotheses. Subsequent sections present preliminary descriptive evidence, describe the empirical methodology and variables, and report results. The final sections discuss the findings and conclude the study.

## R&D BY U.S. PETROLEUM FIRMS

### Data

The U.S. Department of Energy (DOE) has collected uniquely detailed information on the R&D expenditures of the 26 largest U.S. energy firms (primarily petroleum companies) beginning in 1974. The data base includes the major domestic petroleum producers and refiners, plus two railroad companies that are major energy producers.<sup>5</sup>

<sup>4</sup> Because Henderson and Cockburn have output data, they test for economies of scale in R&D. My data on inputs do not permit such a test.

<sup>5</sup> The DOE chose the 26 companies in the data base from the top 50 publicly owned domestic crude oil producers. Each firm in the data base had at least 1 percent of either the production or reserves of oil, gas, coal, or uranium; or 1 percent of oil production, refining capacity, or petroleum product sales in 1976 (U.S. Department of Energy, 1982). The companies in the sample are: Amerada Hess, American Petrofina, Ashland, Atlantic Richfield, Burlington Northern, Cities Service, Coastal Corp., Conoco, Exxon, Getty Oil, Gulf Oil, Kerr-McGee, Marathon Oil, Mobil, Occidental, Phillips Petroleum, Shell Oil, Standard Oil of California, Standard Oil Company (Indiana), Standard Oil Company (Ohio), Sun Company, Superior, Tenneco, Texaco, Union Oil of California, and Union Pacific.

For each firm, the Financial Reporting System (FRS) of DOE contains an annual breakdown of R&D expenditures by type of business application (e.g., oil and gas recovery, refining). This breakdown includes expenditures on more speculative types of R&D, such as that related to gasification of coal or production of oil from shale, for which the companies do not have well-developed businesses and for which output and revenue therefore are minimal. In addition, the FRS data include firm-level assets, sales revenues, and some other balance sheet information broken down by type of business application. Because the data are confidential, only summary statistics and grouped data can be reported.<sup>6</sup>

The statistical analysis in this study covers the period 1976 through 1981. The data base lacks information from 1974 (the first year in the data base) and 1975 for some variables used in the empirical analysis. In addition, several large companies in the data base merged with one another between 1982 and 1984. Because the mergers may have altered the merged companies' R&D expenditures in ways unrelated to the hypotheses tested here (perhaps for several years following the merger), the statistical analysis terminates in 1981.

### Historical context

The time period 1976–81 was unique in the history of the U.S. oil industry. Two major oil price increases—one in 1973–74 and a second in 1978–79—and the increased power of OPEC caused the industry to forecast increasing energy prices into the foreseeable future (Helfat, 1988). As a result, the major U.S. energy companies increased their expenditures on alternative fuels technologies from previously low levels that had prevailed from the end of World War II until the early 1970s. The companies believed that with major alterations, these technologies could become cost competitive with conventional crude oil and refined oil products then subject to price increases and supply restrictions caused by

OPEC. After real oil prices peaked in 1980 and dropped steadily until 1987, spending on alternative fuels technologies also dropped to, and remained at, low levels as well. Because the oil companies spent substantial sums on alternative fuels R&D only during the middle to late 1970s and early 1980s, this period provides a unique opportunity to examine the impact of complementary know-how and other assets on dynamic knowledge accumulation via R&D in these speculative technologies.

The oil supply shortages and price increases caused by OPEC offered an unexpected product–market diversification opportunity in synthetic fuels to U.S. petroleum firms. In order to take advantage of the opportunity, the companies first had to perform substantial amounts of R&D and testing to commercialize the technologies. Although the petroleum industry as a whole spent relatively little on synthetic fuels R&D between the end of World War II and the early 1970s, some firms steadily conducted research on one or more of the technologies.<sup>7</sup> When the oil crisis materialized in the 1970s, firms with greater prior technological development of synfuels had an advantage: since organizational and technological knowledge acquisition is cumulative (Cohen and Levinthal, 1990; Dosi, Teece, and Winter, 1992; Nelson and Winter, 1982), and since many of the technologies were proprietary, these firms had less far to go in commercializing the technologies. Some of the firms also had diversified into nonoil energy sources like coal, which could be used not only directly as an energy source but also as the raw material for synthetic fuels. Additionally, as will be discussed in detail shortly, synthetic fuels utilize technologies similar to those used in the companies' main oil business. The companies therefore could draw on their oil-related knowledge in developing synthetic fuels.

### Oil company R&D and businesses

During the period 1976–81, the energy-related R&D activities of the FRS companies consisted of two sorts of endeavors: those related to con-

<sup>6</sup> Most companies publicly report only total annual R&D expenditures, with no breakdown by type of business application. The FTC line of business data contain firm-level R&D expenditures at approximately the 3½-digit SIC code level, but even these data often do not contain a very fine breakdown of R&D related to new technologies in fledgling (or even as yet nonexistent) lines of business.

<sup>7</sup> In the absence of strong economic incentives prior to the 1970s, the reasons why some firms conducted synfuels R&D and others did not may have had to do with the judgments of individual corporate and R&D managers, combined with different levels of diversification into nonoil energy sources.

ventional, established technologies, and those related to technologies still under development. Firms undertook R&D on the conventional technologies in order to make incremental improvements to current products and processes. Firms that undertook R&D on the less developed technologies sought major technological improvements that would make the alternative fuels cost competitive with conventional fuels. Table 1 lists each of the R&D categories in the FRS data base, summarizes the types of technology involved in each R&D application, and shows whether the R&D involved conventional technologies, less developed technologies, or both. Table 2 lists the primary established businesses of the FRS firms and the nature of the main technologies used in each business for the period 1976–81. (Not all

FRS firms engaged in all businesses listed in Table 2.) As the exhibits indicate, the firms undertook a range of R&D projects to support existing as well as potential new businesses.

The FRS firms' alternative energy R&D consisted primarily of R&D on synthetic fuels from coal, oil shale, and tar sands. Of the three, the firms spent a disproportionately large amount on coal gasification/liquefaction R&D (nearly six times the R&D expenditures for either oil shale or tar sands from 1976 through 1981). By focusing on one technology—namely coal gasification/liquefaction, which the large R&D expenditure levels suggest the companies deemed to hold much promise—this study can examine the influences on dynamic capability accumulation in detail.

Table 1. Energy-related R&D applications in the FRS data, 1976–81

R&D application	Stage of development <sup>a</sup>	Main types of technological knowledge	Examples of applications
Oil and gas recovery	C	Resource location and extraction	Well drilling
	L		Enhanced oil recovery to extract additional crude oil from existing wells
Refining	C	Refining technology	Oil refinery processes and products
Coal gasification/liquefaction	L	Refining technology	Create natural gas and refined oil product substitutes
Other coal	C	Resource location and extraction	Coal mining
	L	Pipeline technology	Coal slurry pipelines
Nuclear	C	Resource location and extraction	Uranium mining
	L	Fuel processing	New uses of nuclear fuels
Oil shale	L	Resource location and extraction Refining technology	Extraction of shale and processing into crude oil substitutes
Tar sands	L	Resource location and extraction Refining technology	Extraction of tar sands and processing into crude oil substitutes
Geothermal	L	Resource location, extraction and processing	Produce electricity from underground steam heat
Solar	L	Solar cell technology	Produce electricity from solar cells

<sup>a</sup>C = conventional technology; L = less developed technology. Stage of development refers to the years 1976–81. Note: Some FRS firms also conducted R&D related to petrochemicals, which utilizes refining technology. The FRS data base does not separate petrochemical R&D expenditures from other nonenergy R&D.

Table 2. Businesses of FRS firms, 1976–81

Business	Primary technological knowledge
Crude oil and natural gas exploration and production	Natural resource location and extraction
Crude oil refining	Refining technology and plant operation
Petrochemical production	Refining technology and plant operation
Transportation (oil and gas pipelines; marine tankers and barges)	Pipeline and marine operations
Coal mining	Resource location and extraction
Other mineral mining (e.g., copper, gold)	Resource location and extraction

### Coal conversion technology

The coal conversion technologies of coal gasification and liquefaction have the potential to produce a natural gas substitute of pipeline quality (via gasification) or to produce substitutes for traditional refined oil products (via liquefaction) (Helfat, 1988). The basic science underlying coal conversion technology dates from 1670, when a Yorkshire clergyman named John Clayton generated a luminous gas by heating coal in a chemical retort (Federal Energy Administration, 1974). Larger-scale production began in Germany in the early 1900s. Oil companies have long had a general knowledge of the technology.

Both gasification and liquefaction technologies have first- and second-generation processes (Helfat, 1988). Firms in Europe and South Africa have used the first-generation Lurgi gasification process to produce low and medium Btu synthetic natural gas commercially. The Lurgi process is costly, however, and low Btu fuel gas has limited usage. A first-generation liquefaction technology such as Fischer-Tropsch also has high costs; in the 1970s, companies did not consider the process to be economically feasible in the foreseeable future. Researchers working on second-generation coal conversion technologies aimed to create more efficient, lower-cost processes, and to produce more widely usable products. For example,

with the addition of a methanation step, the Lurgi process could produce high Btu pipeline quality gas commercially.

Both coal gasification and liquefaction rely on refining technology. A coal conversion plant has many features in common with an oil refinery, which essentially boils crude oil in the presence of a catalyst to distill different fractions of the oil, producing various refined oil products. The technological commonalities between coal conversion and oil refining include high-temperature and high-pressure treatment of hydrocarbon fluids, catalytic processing of hydrocarbons, and fluidized bed design and hydrogenation (Teece, 1980; Federal Energy Administration, 1974). In coal liquefaction, for example, hydrogenation involves adding hydrogen to coal under high temperatures and high pressures in the presence of a catalyst, to produce liquid fuel. Coal conversion also has few know-how complementarities with petroleum firm technologies other than refining.<sup>8</sup>

### DYNAMIC CAPABILITY ACCUMULATION VIA COAL CONVERSION R&D

At least two sorts of complementary assets might have affected the extent to which firms undertook coal conversion R&D in response to rising oil prices. These assets are: (1) refining-based technological knowledge within the firm, which may produce economies of scope; (2) assets which the firm could utilize in commercializing the outcome of coal conversion R&D. The following discussion deals with each of these factors in turn, and also considers additional resources and knowledge available to the firms which might have affected coal conversion R&D.

#### Economies of scope and know-how complementarities in R&D

Economies of scope in R&D are likely to be greatest when speculative technologies draw on knowledge related to established technologies, for the following reasons. Because a speculative tech-

<sup>8</sup> In situ (within the site) production of coal fluids also potentially could utilize oil recovery technology (Teece, 1980). This approach to coal conversion, however, was not pursued heavily by most of the oil companies.

nology has less of an accumulated knowledge base on which to draw than does an established technology, a firm conducting R&D in a speculative technology may rely more heavily on knowledge acquired from R&D and operations in technologically related business applications. Reliance on R&D and other knowledge in related established technologies, rather than in related but less well-developed technologies, may provide the greatest potential for scope economies: more speculative technologies by definition have yet to prove reliable and therefore may have less knowledge usable in related business applications.

Economies of scope in and of themselves do not imply that production of multiple outputs from common inputs should take place within a single firm (Teece, 1980). Intrafirm production of more than one output using common inputs is economically efficient when the transaction costs of using the market to exchange inputs exceed governance costs associated with internal firm organization of production (all other things equal, such as production costs) (Williamson, 1975).<sup>9</sup> Teece (1980) observes that contracting problems regarding know-how become particularly severe when parties seek to transfer knowledge gained in established businesses to a new or not well-developed technology. A company would tend to use the firm rather than the market to transfer such knowledge, because the knowledge would be specialized to a new use, raising the possibility of postcontractual opportunism (Klein, Crawford, and Alchian, 1978). The same is true of R&D activities where a firm seeks to apply its proprietary technological knowledge to new or to less well-developed, more speculative types of R&D. This transaction cost argument also applies to knowledge transfer from one speculative technology to another, but as noted previously, economies of scope may be less pronounced.

The foregoing logic suggests that R&D aimed at reducing the cost and improving the technology of coal conversion could benefit from prior

research within the firm related to conventional oil refining, with which coal conversion has technological commonalities. For example, researchers working on improvements to refining technology could temporarily work on coal conversion R&D, bringing with them knowledge of the latest research on refining processes. Researchers who work on refining R&D also could share their findings on a regular basis with those working on coal conversion technologies. Some FRS companies had centralized R&D laboratories, which would have facilitated communication between researchers, and some of the other companies located all of their refining-related R&D in one facility. Thus, firms that had conducted larger amounts of refining R&D would have had a larger stock of complementary knowledge to draw on. All other things equal, these firms might have undertaken larger amounts of coal conversion R&D, since economies of scope could have lowered the costs of R&D needed to commercialize the technology. This reasoning suggests a testable hypothesis:

*Hypothesis 1a: Firms that had larger stocks of knowledge from past refining R&D were likely to have undertaken larger amounts of coal gasification/liquefaction R&D.*

R&D on speculative technologies may draw not only on R&D but also on broader technological competence in established businesses. Techniques used to design, construct, and operate refineries can be applied to R&D on coal conversion technologies and plant design (Teece, 1980).<sup>10</sup> A firm's accumulated refinery assets provide a rough measure of the extent of a firm's experience in utilizing established refinery technologies, which suggests an additional hypothesis analogous to Hypothesis 1a:

<sup>9</sup> Williamson (1979, 1985) argues that contracting problems and thus transactions costs increase in severity the more knowledge is specialized to a particular application. Because a specialized asset has no alternate uses of equivalent value, the asset's owner may be reluctant to enter into a contract governing its use due to the possibility of postcontractual opportunism by the other party. That is, the other party may attempt to not fully honor the terms of the contract, knowing that the owner of the specialized asset has no alternate uses of equivalent value.

<sup>10</sup> The discussion of technological complementarities has omitted any mention of nonenergy R&D, and of R&D related to petrochemicals in particular. The production of petrochemicals utilizes refinery technology; therefore, both petrochemical R&D and assets may have know-how complementarities with coal conversion R&D. Unfortunately, the FRS data do not separate R&D on petrochemicals from other nonenergy R&D. This makes it difficult to directly test hypotheses regarding linkages between petrochemical and coal gasification/liquefaction R&D. In petrochemical production as in coal conversion processes, however, oil refining is the core underlying technology; thus, the most important complementarities between coal gasification/liquefaction R&D and refining technologies are likely to be those related to oil refining.

*Hypothesis 1b: Firms that had larger accumulated refinery assets were likely to have undertaken larger amounts of coal gasification/liquefaction R&D.*

R&D on coal conversion also might benefit from knowledge acquired via prior R&D in technologically related but more speculative technologies although, as noted earlier, economies of scope might be less pronounced. R&D on the processing of synthetic fuels from oil shale and tar sands in part involves extensions of established refinery technology, and thus could have produced some knowledge useful for coal conversion.<sup>11</sup>

*Hypothesis 1c: Firms that had larger stocks of knowledge from past R&D on other synthetic fuels were likely to have undertaken larger amounts of coal gasification/liquefaction R&D.*

Hypotheses 1a, 1b and 1c, although consistent with the arguments given thus far, may not hold if the outputs of coal conversion R&D and of refining R&D, refining assets, or other synfuels R&D were perfect substitutes. For example, some firms with a strong commitment to established refinery technology might have spent less rather than more on coal conversion R&D, if the output of the latter would have cannibalized refinery output. Major coal conversion cost reductions, however, were forecast to require substantial R&D expenditures and to take a number of years (Federal Energy Administration, 1974). In the meantime, refining R&D produced results that firms could utilize more quickly (generally within 1–3 years) in their refining operations (Helfat, 1988). The outputs of R&D on oil refining and coal conversion therefore were not immediate substitutes for one another, which reduces (but does not eliminate) the output substitutability problem for Hypothesis 1a. With regard to refinery assets, the possibility of output substitutability could cause Hypothesis 1b not to hold. Alternatively, firms with greater refinery assets might have viewed coal conversion R&D as a

means both to utilize refinery expertise and provide greater flexibility in meeting future energy demand. Hypothesis 1b therefore could hold even under conditions of long-run output substitutability. With regard to Hypothesis 1c, processing of oil shale and tar sands produces synthetic crude oil, which is not a substitute for synthetic refined oil or natural gas from coal conversion.

Finally, in addition to technologically related R&D, a firm's general expertise in conducting R&D might provide complementary knowledge for coal conversion R&D. Such general expertise, however, has less direct commonality of technical knowledge with coal conversion, and therefore less potential for economies of scope, than do R&D and operations which utilize refining technology. Nevertheless, the empirical analysis will control for the possibility that firms that had larger nonrefining-based R&D capital stocks also undertook larger amounts of coal conversion R&D.

### **Complementary assets for coal conversion commercialization**

The production and delivery of new products and services often require certain complementary assets, typically downstream from the R&D activity (Teece, 1986). In the case of coal conversion, a key asset required for commercialization of the technology is coal. Although the U.S.A. has abundant coal reserves, they are (and were) not necessarily easily available on spot markets, since long-term leases and contracts for coal supply tend to prevail. In their annual reports, some FRS firms expressed interest in coal conversion as a way to exploit their *prior* holdings of coal reserves. Such reserves included coal owned by some firms prior to the 1973–74 embargo, as well as new investments in coal reserves (sometimes via purchases of coal companies) as energy prices rose. Firms that had larger coal-related assets might have undertaken larger amounts of coal conversion R&D in search of uses for their coal in addition to direct mining and sale.<sup>12</sup>

<sup>11</sup> R&D on oil shale and tar sands also has many know-how complementarities with crude oil production technology, in that extraction of oil shale and tar sands deposits utilizes technology relevant to crude oil recovery (Exxon Corporation, 1991; Teece, 1980).

<sup>12</sup> Coal conversion R&D also led some firms to purchase coal reserves in *subsequent* years. The concern here, however, is with the determinants of coal conversion R&D rather than of coal investment.

*Hypothesis 2: Firms that had larger accumulated coal assets were likely to have undertaken larger amounts of coal gasification/liquefaction R&D.*

### **Additional resources and knowledge**

In addition to complementary technological knowledge and physical assets within the firm, at least three other sorts of knowledge or resources may have affected the amount of coal conversion R&D by the oil companies. First, firms' financial resources may have affected the amount of coal conversion R&D. Overall company profits or cash flows may affect the level of R&D activity if, for example, firms are unwilling to share information about proprietary technologies with external capital markets in order to obtain funds for R&D (Teece, 1980; Teece and Pisano, 1994). During a time period when most oil companies had large cash flows due to rising oil prices, however, another factor may have applied: Jensen (1986) has suggested that the oil companies had free cash flows, some of which might have funded additional R&D of all types, including coal conversion R&D.

Secondly, coal conversion R&D by other firms might have influenced each firm's own R&D activity. Spillovers of knowledge from other firms' coal conversion R&D might partially either have substituted for or have been complementary to a firm's own coal conversion R&D (Jaffe, 1986; Levin and Reiss, 1984). The greater is coal conversion R&D by other firms, the greater the potential spillovers. In addition, rivalry in R&D may have caused each firm to determine its level of coal conversion R&D in response to R&D by other firms.

Thirdly, within the firm, the amount of past coal conversion R&D may have influenced the amount of current R&D, as a result of at least two factors: organizational learning and adjustment costs. Both imply that R&D may have a strong inertial component. The cumulative nature of organizational learning implies that firms search 'locally' for new knowledge, in the neighborhood of current knowledge (Cyert and March, 1992; Nelson, 1990; Nelson and Winter, 1982). In searching for new products and processes, a firm does not examine all possible alternatives, for two reasons. First, bounded rationality (Simon, 1978) makes it difficult to uncover all

possible options, and to accurately evaluate their future prospects. Additionally, possession of an accumulated knowledge base facilitates learning related to that knowledge (Cohen and Levinthal, 1990). The importance of local search suggests that past coal gasification/liquefaction R&D would be a primary determinant of current coal gasification/liquefaction R&D (Nelson and Winter, 1982).

Adjustment costs also imply that the amount of past R&D may affect current R&D. Adjustment costs stem from difficulties firms face in altering the level of R&D activity in the short run, due to either capital or labor market imperfections. Any restrictions on external funding available to firms, due to capital market imperfections, make it difficult for firms to expand R&D quickly if they lack sufficient internal funds. Although the latter may not have constituted a difficulty for the oil companies, any shortages of research personnel could have affected the firms' ability to quickly increase R&D. (Labor market imperfections also may make firms reluctant to fire research personnel, especially if the workers require firm-specific knowledge, which makes training of new workers expensive; Grabowski, 1968; Himmelberg and Petersen, 1991.) Any such difficulty in quickly and easily altering R&D activity implies that the level of past R&D affects the current level.

### **PRELIMINARY EVIDENCE**

Of the FRS companies, not only many of the oil companies but also the railroad companies either increased their interest in or began actively exploring coal gasification/liquefaction technology in the 1976–81 period examined here (Annual Reports for Burlington Northern and Union Pacific, 1976–81).<sup>13</sup> Descriptive information from company annual reports indicates that FRS companies especially active in pursuing coal gasification/liquefaction technology included: Ashland, Atlantic Richfield, Cities Service, Conoco, Exxon, Gulf, Kerr-McGee, Mobil, Occidental, Phillips, Standard Oil of California, Standard Oil of Indiana, Tenneco, and Texaco (Annual Reports, 1976–81, of the FRS companies). Many

<sup>13</sup> The railroad companies hoped eventually to use their large coal reserves as raw material for coal conversion plants.



of these companies entered into joint ventures with the U.S. Department of Energy, the Electric Power Research Institute (a private organization funded primarily by utility companies), or other utility or energy companies (including some FRS companies) to develop various coal gasification and liquefaction technologies. Frequently, the FRS companies had proprietary technologies under development. As noted earlier, when the 1973–74 OPEC oil embargo occurred, some FRS firms were further along in coal gasification/liquefaction development than others. In coal liquefaction, for example, Ashland, Atlantic Richfield, and Cities Service had conducted R&D on the H-Coal process in the 1960s (and the 1950s in the case of Cities Service) (Crow *et al.*, 1988). Conoco also had pursued development of its Consol Synthetic Fuel Process for coal liquefaction since the 1960s, and Gulf Oil had pursued development of the Solvent Refined Coal Process (U.S. Senate, 1977, 1981). Exxon had worked on the development of its Donor Solvent Process for coal liquefaction prior to the embargo as well (Crow *et al.*, 1988). Not surprisingly, these companies continued research on these processes after the embargo (Crow *et al.*, 1988; U.S. Senate, 1979).

Unfortunately, from publicly available sources it is difficult to obtain a comprehensive description of all oil company coal gasification/liquefaction R&D prior to 1973. (The same is also true after 1973, although more information is available.) It is even more difficult to obtain publicly available information regarding the impact of refining know-how on coal gasification/liquefaction R&D, either before or after the embargo. The available information, however, is consistent with a role for know-how complementarities. For example, in developing the Donor Solvent Process, Exxon attempted to incorporate equipment that was as similar as possible to that used by oil refineries, in order to reduce equipment costs (Crow *et al.*, 1988). Kerr-McGee, in its 1980 Annual Report to stockholders, stated that its ‘critical solvent deashing’ technology to remove ash from liquefied coal ‘evolved from Kerr-McGee’s research on petroleum refining.’ In 1975, Standard Oil of California’s Annual Report announced the completion of its new synthetic fuels research laboratory adjacent to its oil refinery in Richmond, California, also the site of the company’s oil refining

R&D lab. (Standard Oil located its other R&D labs elsewhere.) And in Gulf’s 1977 Annual Report to stockholders, the company cited its combined expertise in ‘coal gasification and liquefaction, catalytic processes and petroleum refining.’ As noted earlier, Gulf had previously undertaken research on the Solvent Refined Coal liquefaction process (Gulf Oil, 1974; Crow *et al.*, 1988).

The foregoing examples suggest the importance to coal gasification/liquefaction R&D of know-how complementarities with oil refining technology. In contrast, neither company annual reports nor articles in technical and trade journals consulted (such as the *Oil and Gas Journal* and *Hydrocarbon Processing*) mention know-how links between coal conversion and other synthetic fuels (oil shale and tar sands) technologies for the 1976–81 period. Annual reports do indicate, however, that most of the companies that performed coal conversion R&D also performed some sort of other synthetic fuels R&D for at least part of the 1976–81 period. Additionally, the annual reports usually indicated that companies performing coal conversion R&D had coal reserves or guaranteed sources of coal.

Data on the FRS firms’ R&D activities provide additional descriptive information relevant to this study. Table 3 reports the number of FRS firms conducting coal gasification/liquefaction R&D, oil refining R&D, other synfuels R&D, or any R&D at all, for each of the years 1976 through 1981. In addition, the table presents annual R&D expenditures (in current and constant dollars) and annual mean R&D intensities for coal gasification/liquefaction, refining, other synfuels, and total firm R&D by the FRS companies. Finally, Table 3 reports average annual percentage changes during the period for all variables in the table.

Table 3 reveals that the FRS firms spent substantial amounts on coal gasification/liquefaction R&D from 1976 to 1981; such R&D equaled approximately half the amount spent on refining R&D. In addition, R&D expenditures for coal gasification/liquefaction in real dollar terms rose at an average annual rate of almost 37 percent; mean annual R&D intensity also rose substantially at an average annual rate of 27 percent. This rise in R&D expenditures was accompanied by an increase in the number of firms conducting coal gasification/liquefaction R&D from 13 to

Table 3. Combined FRS company R&amp;D expenditures, 1976–81

Year	No. of firms with positive R&D expenditures <sup>a</sup>	Total R&D expenditures (current \$, million \$)	Total R&D expenditures (constant 1981 \$, million \$)	Mean R&D intensity <sup>b</sup>
<i>Coal gasification/liquefaction R&amp;D</i>				
1976	13	43	64	0.00176
1977	14	82	114	0.00308
1978	14	146	190	0.00495
1979	14	175	209	0.00446
1980	17	188	206	0.00362
1981	18	<u>268</u>	<u>268</u>	0.00466
Total		902	1051	
Average annual percent change	7.00 percent	39.09 percent	36.69 percent	27.14 percent
<i>Refining R&amp;D</i>				
1976	17	187	276	0.00767
1977	17	219	306	0.00821
1978	16	254	330	0.00862
1979	18	273	327	0.00695
1980	19	359	393	0.00692
1981	17	<u>468</u>	<u>468</u>	0.00813
Total		1760	2100	
Average annual percent change	0.33 percent	20.49 percent	11.41 percent	1.94 percent
<i>Other synthetic fuels R&amp;D (oil shale and tar sands)</i>				
1976	14	21	31	0.00086
1977	16	23	32	0.00086
1978	17	26	34	0.00088
1979	17	41	49	0.00104
1980	16	55	60	0.00106
1981	18	<u>153</u>	<u>153</u>	0.00266
Total		319	359	
Average annual percent change	3.18 percent	58.22 percent	46.14 percent	34.67 percent
<i>Total firm R&amp;D</i>				
1976	22	907	1340	0.0372
1977	22	1021	1425	0.0383
1978	21	1283	1668	0.0435
1979	22	1566	1874	0.0399
1980	23	2034	2226	0.0392
1981	24	<u>2820</u>	<u>2820</u>	0.0492
Total		9631	11,353	
Average annual percent change	1.82 percent	25.76 percent	16.24 percent	6.30 percent

<sup>a</sup>Total number of firms in the sample = 26.

<sup>b</sup>R&D expenditures divided by total firm sales for 26 firms in the sample combined.

Data source: Financial Reporting System, Energy Information Administration, U.S. Department of Energy.

18, although most of the increase occurred in the last 2 years of the sample. R&D on other synfuels also increased a great deal, at a 46 percent average annual rate for real expenditures and a 35 percent rate for R&D intensity. The number of firms conducting such R&D rose as well, from 14 to 18.

In contrast, Table 3 also shows that refining R&D expenditures rose over the period at a lower annual average rate of 11 percent in real dollar terms. Neither the number of firms conducting refining R&D nor the mean R&D intensity for refining display more than a slight average annual increase. A similar pattern holds for total firm R&D spending: although most firms in the sample conducted R&D of some type during the period, and although real R&D expenditures rose at an average annual rate of 16 percent, the average annual increase in the number of firms conducting R&D and in the mean R&D intensity amounted to much less (1.8 percent and 6.3 percent respectively).

The expenditure data in the table indicate that, as suggested in the introduction, during a time period of historically high oil prices, the major oil companies greatly increased spending on synthetic fuels R&D. Furthermore, the companies allocated a disproportionately large share of such expenditures to coal conversion R&D. In what follows, regressions provide statistical evidence relevant to the question of whether the firms sought to benefit from complementary refining-based know-how and coal assets as they increased coal conversion R&D.

## EMPIRICAL METHODOLOGY AND VARIABLES

Regressions which test the hypotheses advanced earlier utilize annual firm-level coal conversion R&D spending (transformed as indicated below) as the dependent variable, a proxy measure of the amount of R&D activity. On the right-hand side, the regressions include variables that reflect complementary know-how (i.e., the firm's stock of refining R&D capital, refinery assets, and other synfuels R&D capital), and complementary coal assets. Additional right-hand side variables reflect the other sorts of resources and knowledge discussed earlier, namely, a firm's total non-refining-related R&D capital stock, other firms' coal con-

version R&D capital stocks, the firm's own past coal conversion R&D, and financial resources.

The analysis also controls for three factors, not yet discussed, that do not fall into the category of resources or knowledge, but which might have affected coal conversion R&D spending. These factors are: firm size, oil price, and idiosyncratic firm effects. By controlling for firm size, the analysis accounts for the likelihood that regardless of know-how and other asset complementarity, larger firms spent more on coal conversion R&D than did smaller firms. Secondly, higher energy prices almost surely caused coal conversion R&D expenditures to increase as anticipated future prices (and thus, profits) of the potential energy products from the R&D also rose (Helfat, 1988).<sup>14</sup> With regard to firm effects, the top management or R&D personnel of individual firms may have had idiosyncratic preferences that affected coal conversion R&D spending. In addition, a firm's organizational form may have affected the strength of the know-how complementarities between coal conversion R&D and refining-based knowledge. For example, the extent of communication between researchers may depend on the proximity of the firm's refining and coal conversion R&D labs. By controlling for organizational factors which remained fixed during the 1976–81 period, the inclusion of firm effects in the analysis makes it more likely that any statistical relation between coal conversion R&D and variables used as proxies for complementary knowledge reflect technological know-how rather than organizational form.

The remainder of this section describes the regression methodology and the construction of the variables. The FRS data base provides all of the data, with the exception of publicly available oil price information.<sup>15</sup>

<sup>14</sup> Technological opportunity, another possible determinant of coal conversion R&D spending, changed little from the 1960s through the early 1980s. Additionally, government subsidies for synthetic fuels research might have increased expenditures (including the subsidies) on coal conversion R&D, although in conversations with the author some managers indicated that they would have undertaken the government funded projects in the absence of federal funding (Helfat, 1988). An alternate empirical approach of incorporating year dummy variables rather than oil annual prices into the regressions changes the results little.

<sup>15</sup> Unfortunately, it is not possible to use a production function approach to directly estimate petroleum firm economies of scope related to coal conversion R&D. Because the firms have yet to commercialize the technology, data on petroleum

### Regression methodology

Some firms had zero expenditures on coal gasification/liquefaction R&D for some or all years in the sample, as Table 3 shows. Sixty-six of the 156 coal gasification/liquefaction R&D observations are zero. When observations of the dependent variable are 'censored,' tobit regression is appropriate. (Ordinary least squares (OLS) will yield biased and inconsistent estimates of the regression coefficients; Maddala, 1983.) The independent variables in a tobit regression affect both the probability that the dependent variable exceeds zero (or other threshold value) and the value of the dependent variable if it exceeds zero. The hypotheses implicitly deal with both the probability of conducting coal conversion R&D and the amount of R&D if positive. For example, Hypothesis 1a includes the possibility that firms that had low refining R&D capital stocks may have undertaken no coal conversion R&D at all. The analysis therefore includes the zero values of coal conversion R&D in the sample.

The regressions are estimated using SAS version 5, the only software available for use with the FRS data. Because SAS version 5 does not have a tobit procedure, the estimation uses a program in SAS matrix language (adapted from one in a SAS User's Guide) to compute tobit maximum likelihood estimates using Fair's technique (Fair, 1977). In tobit regression, it is difficult to correct for any serial correlation of the residuals. Standard corrections used in OLS involve some form of first-differencing of the dependent variable, and therefore do not apply in tobit analysis. (Values of the transformed dependent variable could be negative, which tobit regression cannot accommodate.) Given the difficulty of correcting for serial correlation, this study instead tests for autocorrelation of the residuals, and discusses any implications for the parameter estimates.

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firms' output reflect little output from coal conversion. This study also does not utilize a structural econometric model of the determinants of companies' R&D expenditures. Such a model would involve the complex task of mapping the sometimes intertwined determinants of a firm's multiple R&D applications, and the data requirements would be extensive. Instead, the regressions account for as many potential determinants of coal conversion R&D spending as possible; the variables are constructed to limit potential simultaneity.

The regression estimation incorporates the following assumption regarding firm behavior: at the start of each year, managers made decisions to expand their firms' stocks of knowledge pertaining to coal conversion technology, based on the information and resources available at the time. Although the firms might have altered spending on the margin during the year, the primary budgetary allocations are presumed to have occurred at the start of the year. This approach seems consistent with capital budgeting behavior in general (Bromiley, 1986). Therefore, all right-hand side variables (except dummy variables and the constant term) are lagged 1 year. Such a procedure has the additional advantage that it limits potential simultaneity insofar as possible.

### Variables

Several regressions are estimated to test the hypotheses. All of the regressions use annual firm coal gasification/liquefaction R&D expenditures divided by sales revenue for the entire firm (also termed coal gasification/liquefaction R&D intensity hereinafter) as the dependent variable. Since within an industry, R&D expenditures tend to rise linearly with sales revenues at the business unit and the firm level (Scherer, 1992, 1980), researchers frequently use an R&D intensity variable (R&D expenditures divided by sales) to directly control for an effect of organization size on R&D expenditures. In this study, R&D is divided by firm rather than business unit sales, because even the most advanced firms' coal conversion operations had not progressed beyond the pilot plant stage and therefore had minimal revenues. The correlation between coal conversion R&D spending and total firm sales was 0.76 (significant at the 0.01 level) for the 1976–81 period. An alternative procedure to account for the impact of firm size on R&D expenditures might involve including sales revenue as one of several independent variables in a regression where R&D spending on coal conversion is the dependent variable. Unfortunately, such a procedure creates practical problems of multicollinearity, because sales revenues are highly correlated with most of the factors that might have affected coal conversion R&D spending.

The right-hand side of the regressions includes several R&D capital stock variables (described in

more detail below) as proxy measures for knowledge accumulated via R&D. These variables, computed using a perpetual inventory approach, exclude current year R&D spending so that the R&D capital stocks reflect knowledge accumulated as of the start of each year.<sup>16</sup> As with coal conversion R&D expenditures, this study divides R&D capital stocks by total firm sales in order to control for firm size. Hypotheses 1a and 1c do not exclude the possibility that because larger firms tend to conduct greater amounts of complementary refining-based R&D, they will produce greater refinery-related technological knowledge and therefore will conduct greater amounts of coal gasification/liquefaction R&D. Since know-how complementarities may have effects in firms of all sizes, however, it is useful to examine know-how complementarities irrespective of firm size.

The individual right-hand side variables included in the regressions are described below. Table 4 provides a summary list and definitions of the variables. All within-firm variables include a firm sales revenue divisor (denoted by the term 'intensity' in the variable names), since all of the R&D capital stocks, physical assets, and other firm resources are highly correlated with firm size.<sup>17</sup>

#### *Complementary knowledge*

- *Refining R&D Capital Stock Intensity*—lagged end-of-year value (Hypothesis 1a)
- *Refinery Asset Intensity*—lagged end-of-year value (Hypothesis 1b)

<sup>16</sup> The FRS data base contains R&D expenditures for all firms and types of R&D used in this study beginning in 1974. Following Hall *et al.* (1988), each start-of-period (i.e., beginning of 1974) R&D capital stock was computed by dividing real R&D expenditures in 1974 by the sum of a depreciation rate of 'R&D capital' (here set equal to 10 percent) plus a growth rate of expenditures since minus infinity. (On the assumption that R&D expenditures before the 1973–74 embargo grew roughly at the same rate as sales, the growth rate was set equal to 3.5 percent, a level slightly above the approximately 3 percent productivity growth rate of the U.S. economy in the late 1960s.) Each start-of-year R&D capital stock was computed as the sum of the depreciated values (using the 10 percent rate) of the start-of-period R&D capital stock and annual real R&D expenditures from 1974 through the end of the prior year.

<sup>17</sup> For example, the correlation between refining R&D and firm sales is 0.89, significant at the 0.01 level.

- *Other Synfuels R&D Capital Stock Intensity*—lagged end-of-year value (Hypothesis 1c)

#### *Complementary physical assets*

- *Coal-related Asset Intensity*—lagged end-of-year value (H2)

#### *Other knowledge and resources*

- *Lagged Dependent Variable*—The effects of cumulative learning in R&D and 'local' search for new knowledge can be modeled as a first-order Markov process where the cumulative impact of past R&D spending is embodied in last year's R&D activity, which in turn affects current R&D activity (Nelson and Winter, 1982). The possible influence on current R&D expenditures of costs of adjusting spending from the prior level also suggests that the regression should include a 1-year lag of coal conversion R&D intensity.
- *Other Firms' Coal Conversion R&D Capital Stock*—Lagged total FRS firm coal conversion R&D capital stock minus own-firm coal conversion R&D capital stock serves as a proxy for external knowledge spillovers and also perhaps for an effect of R&D rivalry. The variable is not adjusted for firm size, since the extent of external knowledge spillovers or R&D rivalry would tend to vary with the total R&D capital stock rather than with the R&D intensity of other firms.<sup>18</sup>
- All own-firm R&D capital stock intensity other than that for coal conversion, refining, and other synfuels, split into: *Oil and Gas Recovery R&D Capital Stock Intensity* and *Other R&D Capital Stock Intensity*—From 1976 through 1981, the FRS companies as a group spent more on oil and gas recovery R&D than on oil refining R&D; the technological know-how relationships discussed earlier, however, suggest that coal

<sup>18</sup> The division of this variable by sales revenues, however, does not change the empirical results. With regard to R&D rivalry, given the slow pace of technological advance in this industry, any effect of other firms' R&D on own-firm R&D may occur with a lag. Since this study does not focus on external R&D spillovers and rivalry, the proxy variable is designed only as a rough indicator. The variable does not account for coal conversion R&D by non-FRS firms, nor does it account for the size distribution of R&D spending among firms.

Table 4. Variable names<sup>a</sup>

Variable	
COALRD	Coal gasification/liquefaction R&D intensity (R&D expenditures divided by firm sales)
REFRDCAP	Refining R&D capital stock intensity, end of prior year <sup>b</sup>
LAGCLRD	Lagged (1-year) coal gasification/liquefaction R&D intensity
CLASSET	Coal-related asset intensity, lagged 1 year <sup>c</sup>
OILRDCAP	Oil and gas recovery R&D capital stock intensity, end of prior year <sup>b</sup>
SYNRDCAP	Other synfuels (oil shale and tar sands) R&D capital stock intensity, end of prior year <sup>b</sup>
OTHRDCAP	R&D capital stock intensity for the remainder of the firm's R&D (total firm R&D less that for coal conversion, refining, oil and gas recovery and, other synfuels), end of prior year <sup>b</sup>
REFASSET	Refining asset intensity, lagged 1 year <sup>c</sup>
PRICE	Annual retail price of No. 2 fuel oil ( $\text{\$/gallon}$ ), lagged 1 year (divided by 100 to scale the coefficient estimate appropriately)
INDRDCAP	Industry (i.e., total FRS company) coal conversion R&D capital stock minus own-firm coal conversion R&D capital stock, end of prior year (divided by 1,000,000 to scale the coefficient estimate appropriately) <sup>b</sup>
PROFIT	Total firm pre-tax operating income divided by firm sales, lagged 1 year

<sup>a</sup>The term 'intensity' denote division by total firm sales.

<sup>b</sup>Footnote 16 in the text describes the computation of the R&D capital stocks.

<sup>c</sup>Assets include the book value of property, plant and equipment adjusted for depreciation, depletion, amortization, and write-offs, plus investments and advances to unconsolidated affiliates.

gasification/liquefaction R&D does not have strong know-how linkages to oil and gas recovery R&D. A finding that refining R&D capital stock was positively related to coal conversion R&D, but that oil and gas recovery R&D capital stock was not, would provide additional support for Hypothesis 1a.<sup>19</sup> The capital stock variable for the remainder of the firm's R&D accounts for the possible influence of general R&D expertise.<sup>20</sup>

- *Operating Income Intensity*—lagged year-end value of pre-tax income divided by sales, a

proxy for financial resources. (The FRS data base did not contain data on cash flows, an alternative measure, for 2 of the 6 years in the sample.)

#### *Control variables*

- *Oil Price*—lagged annual constant dollar price of No. 2 fuel oil, a refined oil product.<sup>21</sup>
- *Firm Dummy Variables* control for idiosyncratic firm-specific factors that did not change during the sample period (termed 'fixed effects'),

<sup>19</sup> As was true of the output of refining R&D, the output of oil and gas recovery R&D likely would have been complementary to rather than a substitute for the output of coal conversion R&D.

<sup>20</sup> As noted in an earlier footnote, in the FRS data base petrochemicals R&D is not separated from other nonenergy R&D. The other R&D capital stock intensity variable therefore includes petrochemicals R&D, which may have know-how complementarities with coal conversion R&D that cannot be ascertained in this study.

<sup>21</sup> Most coal gasification/liquefaction research aimed to produce substitutes for heavy refined oil products such as fuel oil and for natural gas. Natural gas in turn is a substitute for fuel oil. During the time period studied here, natural gas prices were scheduled for gradual deregulation. By the time coal conversion R&D would have resulted in new plants, deregulated natural gas prices would have applied (Helfat, 1988); the latter would have tended to converge with fuel oil prices because the products are substitutes.

including any aspects of each firm's organizational structure that remained fixed through time. Most of the major restructuring by the oil companies occurred subsequent to the 1976–81 time period examined here, as a result of the mergers in the early 1980s and the drop in oil prices in the early and mid-1980s. The dummy variable for one firm (arbitrarily chosen) is excluded from the regressions; the constant term estimates the effect of the excluded firm on the dependent variable.

The following section reports two sets of regressions: one set which includes the lagged dependent variable but no firm dummy variables, and a second set which does the reverse. Firm dummy variables are not included in regressions that include the lagged dependent variable, since this would produce inconsistent estimates of the coefficient on the lagged dependent variable (Holtz-Eakin, Newey, and Rosen, 1988). In all other respects, the two sets of regressions are identical.

Both sets of regressions lend themselves to a dynamic interpretation. The inclusion of a lagged dependent variable creates a partial adjustment model (Maddala, 1977) wherein the firm has a desired level of coal conversion R&D determined by the amount of complementary know-how, assets, and other resources, but cannot achieve the desired level of R&D due to adjustment costs. In the fixed effects regressions, the coefficient estimates reflect relationships within the firms over time.<sup>22</sup>

## EMPIRICAL RESULTS

Table 5 displays simple statistics and Table 6 presents a correlation matrix for all variables in the regressions, other than dummy variables. Table 6 shows that several of the variables have statistically significant correlation coefficients. To address the issue of multicollinearity, whenever two or more variables are individually insignificant

<sup>22</sup> The least-squares dummy variable approach used here is equivalent to estimating a regression of annual changes in the dependent variable on annual changes in the right-hand side variables. The latter approach cannot be used in a tobit regression because it may produce negative values of the dependent variable, which tobit regression cannot accommodate.

Table 5. Simple statistics (156 Observations)

Variable name	Mean	Standard deviation
COALRD	0.000198	0.000390
REFRD CAP	0.00433	0.00453
LAGCLRD	0.000172	0.000355
CLASSET	0.0151	0.0307
OILRD CAP	0.00456	0.00553
SYNRD CAP	0.00223	0.00748
OTHRD CAP	0.0102	0.00907
REFASSET	0.104	0.0600
PRICE	0.668	0.180
INDRD CAP	0.00102	0.00176
PROFIT	0.121	0.0807

cant in the regressions, their joint significance is tested.

Table 7 contains the regression results. In the table, regression #1 includes the lagged dependent variable and all other right-hand side variables described in the previous section except the firm dummy variables. The regression supports Hypothesis 1a: the coefficient on refining R&D capital stock intensity is positive and significant. This result is particularly notable in light of the fact that, not surprisingly, the coefficient on lagged coal conversion R&D intensity is positive and highly significant. That is, even after accounting for the impact of past coal gasification/liquefaction R&D on current R&D, the regressions show a positive relationship between refining R&D capital stock and coal conversion R&D.<sup>23</sup> The only other significant variables are industry coal conversion R&D capital stock (a negative coefficient) and oil price (a positive coefficient). Examination of the residuals does not provide any evidence of heteroscedasticity in the regression. An additional test provides no evidence of serial correlation of the residuals.<sup>24</sup>

<sup>23</sup> Refining R&D in the period examined here also tended to include relatively more product than process R&D (Helfat, 1988). Since it is primarily the process R&D that would have know-how complementarities with coal conversion R&D, the significance of the refining R&D variable is particularly meaningful.

<sup>24</sup> Because each regression includes a lagged dependent variable, the first-order serial correlation coefficient is estimated according to a procedure described in Pindyck and Rubinfeld (1991: 148). The residuals are regressed against a constant term, 1-year lagged residuals, the lagged dependent variable, and the other right-hand side variables in the original regression. The residuals were lagged for each firm separately before pooling. The estimated coefficient on the lagged residuals is insignificant for all regressions which include the lagged dependent variable.

Table 6. Pearson correlation coefficients (statistical significance levels in parentheses)

	COALRD	REFRDCAP	LAGCLRD	CLASSET	OILRDCAP	SYNRDCAP	OTHRDCAP	REFASSET	PRICE	INDRDCAP	PROFIT
COALRD	1.0000* (0.0000)										
REFRDCAP	0.0178 (0.8252)	1.0000* (0.0000)									
LAGCLRD	0.8106* (0.0001)	0.0371 (0.6455)	1.0000* (0.0000)								
CLASSET	0.2168* (0.0066)	-0.1823* (0.0228)	0.2757* (0.0005)	1.0000* (0.0000)							
OILRDCAP	0.1593* (0.0470)	0.3585* (0.0001)	0.1453* (0.0703)	-0.1530* (0.0566)	1.0000* (0.0000)						
SYNRDCAP	-0.1354* (0.0918)	0.3154* (0.0001)	-0.1300 (0.1058)	0.0954 (0.2362)	-0.0051 (0.9493)	1.0000* (0.0000)					
OTHRDCAP	0.1640* (0.0408)	0.3955* (0.0001)	0.1830* (0.0222)	0.2651* (0.0008)	0.0980 (0.2234)	-0.0223 (0.7819)	1.0000* (0.0000)				
REFASSET	-0.0534 (0.5078)	0.2369* (0.0029)	-0.0730 (0.3650)	-0.2992* (0.0001)	0.5438* (0.0001)	-0.2198* (0.0058)	-0.1805* (0.0241)	1.0000* (0.0000)			
PRICE	0.0898 (0.2650)	-0.1235 (0.1246)	-0.0486 (0.5470)	0.0973 (0.2271)	-0.0745 (0.3551)	-0.0724 (0.3692)	-0.0654 (0.4175)	-0.2814* (0.0004)	1.0000* (0.0000)		
INDRDCAP	-0.1897* (0.0177)	-0.1482* (0.0649)	-0.1958* (0.0143)	-0.1059 (0.1883)	-0.1528* (0.0569)	0.0383 (0.6346)	-0.0799 (0.3217)	-0.2835* (0.0003)	0.8486* (0.0001)	1.0000* (0.0000)	
PROFIT	0.0148 (0.8546)	0.1691* (0.0348)	0.0441 (0.5849)	0.2759* (0.0005)	0.1638* (0.0410)	0.5376* (0.0001)	0.0647 (0.4224)	-0.1093 (0.1742)	0.1590* (0.0474)	0.1837* (0.0217)	1.0000* (0.0000)

\*Significant at the 0.10 level or less.



Table 7. Tobit regressions (*t*-statistics in parentheses)

Dependent variable: COALRD						
Independent variables	#1	#2	#3	#4	#5	#6
Constant term	-0.0004** (-2.2419)	-0.0004** (-2.4465)	Constant term included		-0.0004** (-2.2377)	Constant term included
REFRDCAP	0.0166* (1.8672)		0.1205** (2.4851)		0.0197* (1.7036)	0.1304*** (2.6419)
REFASSET	0.0003 (0.3583)	0.0008 (1.1283)	-0.0022 (-1.0840)	0.0002 (0.1208)	0.0002 (0.2774)	-0.0024 (-1.1983)
SYNRDCAP	-0.0206 (-1.3450)	-0.0146 (-1.0343)	0.1111 (1.5978)	0.1251* (1.9225)	-0.0201 (-1.3196)	0.0911 (1.2666)
CLASSET	-0.0007 (-0.4190)	-0.0019 (-1.3220)	0.0357*** (5.9256)	0.0316*** (5.4710)	0.0001 (0.0617)	0.0480*** (4.0472)
OILRDCAP	0.0023 (0.3074)	0.0015 (0.2028)	-0.0145 (-0.3411)	-0.0177 (-0.3867)	0.0024 (0.3295)	-0.0159 (-0.3654)
OTHRDCAP	0.0024 (0.5257)	0.0074* (1.9462)	-0.0036 (-0.1867)	0.0171 (0.9560)	0.0075 (0.2805)	-0.0049 (-0.2542)
INDRDCAP	-0.0007** (-2.1677)	-0.0007** (-2.1256)	-0.0006 (-1.6313)	-0.0006 (-1.6541)	-0.0007** (-2.0810)	-0.0007* (-1.7488)
PROFIT	-0.0003 (-0.5094)	-0.0002 (-0.5062)	0.0019* (1.7496)	0.0029*** (2.9750)	-0.0003 (-0.5265)	0.0026** (2.1025)
PRICE	0.0010*** (3.0006)	0.0010*** (3.0074)	0.0011*** (3.1118)	0.0009*** (2.6676)	0.0010*** (2.9114)	0.0011*** (3.0996)
LAGCLRD	0.9468*** (9.5940)	0.9781*** (10.2287)			0.9594*** (9.2112)	
REFRDCAP × CLASSET					-0.3165 (-0.4216)	-2.6446 (1.2086)
Firm dummy variables			Jointly significant <sup>a</sup>	Jointly significant <sup>a</sup>		Jointly significant <sup>a</sup>
Chi-square statistic	219.923 <sup>a</sup>	219.565 <sup>a</sup>	474.831 <sup>a</sup>	446.762 <sup>a</sup>	220.202 <sup>a</sup>	447.551 <sup>a</sup>
<i>N</i> (all observations)	156	156	156	156	156	156
<i>N</i> (nonzero observations)	90	90	90	90	90	90

\*\*\*Significant at the 0.01 level or less (two-tailed test).

\*\*Significant at the 0.05 level or less (two-tailed test).

\*Significant at the 0.10 level or less (two-tailed test).

<sup>a</sup>Significant at the 0.01 level or less (one-tailed test).

In regression #1, the refining asset and other synfuels R&D capital stock variables lack significance. Both, however, may be correlated with refining R&D capital stock if: (1) firms that had greater refinery operations expertise (and assets) also conducted greater amounts of refining R&D to support those operations; (2) other synfuels R&D drew on firms' refining R&D capital, since other synfuels R&D in part involves refining technology. Table 6 indicates that both the refinery asset and the other synfuels R&D variables have a positive and significant correlation with refining R&D capital stock. A second regression therefore deletes the refining R&D variable from regression #1. In regression #2 in Table 7, neither the refinery asset variable nor the other synfuels R&D variable becomes significant, either individually or together.

In both regressions #1 and #2, the coefficient on the lagged dependent variable does not differ statistically significantly from 1.00. This stability in coal conversion R&D spending impairs interpretation of the results because the coefficients would suggest that refining R&D capital stock is a determinant not only of current but also of past coal conversion R&D. In addition, the lagged dependent variable may capture some of the effects of the lagged asset and R&D capital stock variables.<sup>25</sup>

Two additional regressions, numbered 3 and 4 in Table 7, omit the lagged dependent variable, which also makes it possible to include the firm dummy variables; the regressions mirror regressions #1 and #2 respectively. The refining R&D capital stock variable once again is positive and significant in both regressions #3 and #4. In addition, the coal asset variable becomes significant. The only other variables significant in both regressions are firm profitability and oil price (positive coefficients), industry coal conversion R&D capital stock (a negative coefficient), and the firm dummy variables as a group. (The table does not report coefficient estimates for the individual firm dummy variables, since they are all relative to the omitted firm and do not have meaning in and of themselves. The constant term

also is not reported, since it reflects the effect of the omitted dummy variable.) In regression #4, which excludes refining R&D capital stock, the coefficient estimate for other synfuels R&D capital stock is significant.

The residuals in the two regressions are serially correlated.<sup>26</sup> Since the refining R&D capital stock and coal asset variables are highly significant at the 0.015 and the 0.0001 level respectively, it is likely that these variables still would be statistically significant if the estimates could be corrected for serial correlation. (This logic holds if the error term is uncorrelated with the two variables.) The other synfuels R&D capital stock variable in regression #4, however, is only significant at the 0.06 level, and might not be significant if the regressions were corrected for autocorrelation of the residuals.

The four regressions consistently support Hypothesis 1a regarding the role of refining R&D capital stock. The fixed effects regressions (numbers 3 and 4), which remove any confounding effect of the lagged dependent variable, show strong significance of the coal asset variable in the direction suggested by Hypothesis 2. The other synfuels R&D capital stock variable is significant in one regression, in the direction suggested by Hypothesis 1c. Since the regression does not control for refining R&D knowledge, the significance of the other synfuels variable might reflect the reliance of other synfuels R&D on refining R&D rather than any complementarity of other synfuels R&D with coal conversion R&D.

Given the clear-cut support from the regressions for Hypothesis 1a and Hypothesis 2, an interesting possibility presents itself: possession of refining R&D knowledge and coal assets together rather than separately might matter. Firms that had large coal assets but little refining R&D capability might have performed relatively little coal conversion R&D, for example. Two additional regressions test this supposition: regressions #5 and #6 in Table 7 include an interaction term between refining R&D capital stock and coal assets, in addition to the other variables in regressions #1 and #3

<sup>25</sup> The equations imply that the determinants of lagged coal conversion R&D include 2-year lagged assets and lagged start-of-year R&D capital stock. Thus, the lagged coal conversion R&D variable captures a portion of the lagged asset and R&D capital stock variables.

<sup>26</sup> For each regression, the residuals are lagged 1 year separately for each firm and then pooled. A regression of current on lagged residuals yields a statistically significant autocorrelation coefficient for each of the regressions.

respectively. The interaction term is insignificant, and the statistical significance of the other variables does not change.<sup>27</sup>

## DISCUSSION

Coal conversion R&D intensity rose markedly during the period 1976 through 1981, partly in response to high oil prices, as the positive coefficients on the oil price variable in the regressions indicate. The positive coefficients on the refining R&D capital stock variable suggest that the FRS firms as a group may have sought to benefit from complementary knowledge accumulated from past refining R&D, while increasing coal conversion R&D in response to environmental change. The insignificant coefficients on oil and gas recovery R&D capital stock, which has few know-how complementarities with coal conversion R&D, lend further support to the interpretation that the significance of the refinery R&D variable reflects complementary know-how. In addition, the fixed effects regressions show that within the firms over time, larger coal conversion R&D spending had a positive association with a larger preexisting stock of coal assets, suggesting that the increase in coal conversion R&D during the 1976–81 period was positively related to possession of complementary physical assets. An interaction term between refining R&D capital stock and coal assets lacks significance in the regressions, indicative of a separate rather than a joint relationship of each variable to coal conversion R&D.

The earlier discussion of economies of scope in R&D suggested that know-how complementarity between more established areas of R&D (such as refining) and more speculative R&D (such as coal conversion) would exceed the complementarity between two sorts of speculative R&D (e.g., coal conversion and other synfuels). The results are somewhat consistent with such a proposition. The other synfuels R&D capital stock variable lacks significance, except in a regression which omits the refining R&D capital stock variable. Since the latter might serve as a common knowledge

base for both coal conversion and other synfuels R&D, omission of the refining R&D capital stock variable could cause other synfuels R&D to become significant, even in the absence of know-how complementarity between other synfuels and coal conversion R&D.

The regressions also do not support Hypothesis 1b regarding refining operations expertise. Perhaps the refinery asset variable is not a good proxy for accumulated knowledge of refinery operations. Alternatively, it is possible that any oil refining process developments that the companies sought to utilize in coal conversion R&D stemmed primarily from R&D related to oil refining, rather than from knowledge gained through refinery operations. Output substitutability also could have contributed to the result for refinery assets if a negative effect of output substitutability counteracted a positive effect of know-how complementarities with refining operations.

Of the other firm resources and knowledge that might have affected coal conversion R&D, the variables which account for past coal conversion R&D (lagged dependent variable) and financial resources (profitability) have positive and significant coefficients (the latter in the fixed effects regressions).<sup>28</sup> The regressions do not suggest any know-how complementarity between firm-wide R&D capabilities and coal conversion R&D; the coefficient on the remainder of the firm's R&D capital stock (other than that related to oil and gas recovery or synfuels) is insignificant in all but one regression. The variable reflecting the coal conversion R&D capital stock of other firms has negative and often significant coefficients; this might have resulted if spillovers from other firms' R&D partially substituted for own-firm R&D, or if high levels of R&D capital possessed by others deterred rivalrous R&D spending. Finally, the significance of the firm dummy variables as a group suggests a relationship of idiosyncratic firm-level factors to coal conversion R&D activity.

<sup>27</sup> Additional regressions (not reported here) included interaction terms between coal assets and refining assets, and between coal assets and other synfuels R&D capital stock. These variables also were not significant.

<sup>28</sup> Inclusion of oil price in the regression controls for the possibility that the profitability variable otherwise might reflect the impact of oil prices on operating income.

## CONCLUSION

This study has investigated the role of complementary technological knowledge and physical assets in dynamic capability accumulation. During a unique time period in the petroleum industry, the analysis suggests that as firms raised spending on coal conversion R&D in response to rising oil prices, they may have sought to benefit from complementary oil refining R&D-based knowledge and to exploit complementary coal assets. When real oil prices fell in the 1980s, coal conversion R&D spending by the FRS firms also fell to very small amounts by the end of the decade. The sharp decline in coal conversion R&D suggests that any economies of scope from complementary technological knowledge or any benefits of exploiting complementary coal assets could not make up for the large drop in real oil prices.

The firms in this study were large, often diversified at least within the energy sector of the economy, and conducted primarily applied rather than basic research (U.S. Department of Energy, 1982). With regard to firms' R&D capabilities, one might ask whether smaller, more focused firms can as effectively utilize potential know-how and other asset complementarities, and if not, whether this places smaller firms at a disadvantage both in a dynamic as well as a more static setting. Perhaps smaller firms must concentrate their R&D efforts in areas where knowledge spills more frequently across rather than within firms. Such a possibility of course goes beyond the scope of this study.

More generally, additional empirical research on dynamic capability accumulation is needed. Organizational issues hold particular interest. For example, we need to learn more about the ways in which firms identify and promote opportunities for knowledge and asset sharing across different activities within the firm. Such a task, never easy in a static environment, becomes an even greater challenge as firms compete in increasingly complex and dynamic settings.

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