SYNTHETIC FUELS DEMONSTRATION PROGRAM

by

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I. SYNTHETIC FUELS TECHNOLOGY

Coal is a basic fuel that may be burned directly for heat or may be converted into a variety of synthetic fuels. The basic conversion process involves the reaction of carbon with water and oxygen, possibly under pressure. The range of fuels includes gases, gasoline, benzene, and many others. Most of the processes for converting coal into synthetic fuels produce several of these fuels simultaneously, but in varying proportions. If the products are primarily gases, then the process is called gasification; if the products are primarily liquids, then the process is called liquefaction.

HISTORY

The conversion of coal to synthetic fuels is an old technology. The basic science on which it rests dates back to the late 1600s, when a clergyman reported the generation of a luminous gas when coal was heated in a chemical retort.\(^1\) By the late 19th century "water gas," which is produced by one kind of coal conversion process, was being widely used for lighting purposes. Three gasification processes discovered in Germany in the early 20th century are currently in commercial use: (1) the Winkler process, which is used in 36 plants; (2) the Lurgi process, which is used in about 50 plants; and (3) the Koppers-Totzek process, which is also used in about 50 plants.\(^2\) Large-scale liquefaction of coal began about 1910 with the Fischer-Tropsch process in Germany and is still being used in the SASOL plant in South Africa and other places to produce a variety of synthetic fuels.\(^3\) Because the United States has had abundant supplies of crude oil and natural gas, none of these plants are located in the United States. For the same reason, there has been little effort in the United States


\(^2\) Ibid.

\(^3\) Ibid.
to develop new synthetic fuels processes. However, with the recent large increases in prices for crude oil and natural gas and the looming shortages of these resources, U.S. interest in developing coal conversion technology is growing.

CURRENT ACTIVITIES

Both the federal government and private firms are currently sponsoring developmental efforts to find new coal conversion processes that improve upon the Lurgi, Winkler, Koppers-Totzek, and Fischer-Tropsch methods. The main objective is to reduce the production cost of synthetic fuels from coal enough so that they can compete with fuels from natural sources. Experimentation is being conducted on a large number of new processes, several of which are listed in Figs. 1 and 2.

Experimental work on ten of these processes is being supported by the Coal Conversion Division of the Energy Research and Development Agency. The activities being supported range from research through demonstrations.

This report will consider only the Division's demonstration activities. Although no demonstrations have been completed, developmental work has progressed to the point where several processes are ready for demonstration. The Division's staged approach to process development is sufficiently unusual among all the federal programs included in our overall study of demonstrations to be worth examining even though no demonstrations have been completed.

This section will briefly describe some of the basic characteristics of synthetic fuels processes and summarize the major uncertainties regarding new processes that are inhibiting their widespread commercial use. The second section will briefly describe the current status of the synthetic fuels industry and barriers to the use of this new technology. A description of the kinds of uncertainties that will be addressed through the Coal Conversion Division's demonstration programs in Section III together with the results of Section II, will permit drawing of some conclusions in Sections IV and V on the role of demonstrations in advancing synthetic fuels technology into widespread commercial usage.
Fig. 1 -- Description of coal gasification processes

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+ Processes being developed with support from the Coal Conversion Division of the Energy Research and Development Administration.

**Fig. 2 -- Description of coal liquification processes**

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+ Processes being developed with support from the Coal Conversion Division of the Energy Research and Development Administration.
BASICS OF SYNTHETIC FUELS TECHNOLOGY

All coal conversion processes currently being used or investigated can be broken down into a series of three main stages as diagrammed in Fig. 3: coal preparation, coal conversion, and product cleanup. In addition, coal conversion processes may require other resource inputs (such as oxygen, hydrogen, or steam) and system energy (such as electricity). These two functions are indicated in Fig. 3 as auxiliary stages.

Coal Gasification and Liquefaction

Coal conversion processes differ mainly in the second stage, where the coal is introduced into a reactor that transforms it into a raw mixture of hydrocarbon fuels and other chemical compounds. In gasification processes, the raw products are mainly such gases as methane, carbon monoxide, and carbon dioxide. Methane is usually the desired product because it is a substitute for natural gas, which is almost pure methane. In most gasification processes, the raw product gas contains only a few percent methane, but some produce larger amounts.

A diagram of the physical configuration of the gasifier used in the HYGAS process, which produces 60 to 70 percent methane, is shown in Fig. 4. In liquefaction, the raw products can include a wide range of liquid hydrocarbon fuels and gases. One of these gases is usually methane. Figure 5 shows the flow products in a typical liquefaction process.

Coal Preparation

Prior to being fed into the conversion reactor, the raw coal must be crushed to a desired size, cleaned, and possibly pretreated (by heating) to destroy its coking properties. As a final step, the coal may also be slurried in oil or water, or otherwise prepared, for feeding it into the conversion reactor. Coal feeding is a difficult operation because most of the conversion reactors in the new processes operate at high pressures and are sensitive to fluctuations in the rates of coal input.
Fig. 3 — Stages of coal conversion processes
Fig. 4 -- Gasifier stage: HYGAS pilot gasification plant

Fig. 5 -- Flow diagram of the SRC liquefaction process

SOURCE: Federal Energy Administration, p. 142.
Product Cleanup

Following the coal conversion stage, the raw product is further processed to produce the synthetic fuels. The amount of processing depends on the types of synthetic fuels produced. In low-BTU gasification, the final product gas is piped directly to a nearby electric power plant where minimal processing is required. In high-BTU gasification (the production of pipeline quality gas) or in liquefaction, the amount of processing required is substantial. This processing may involve the separation of the raw product into component gases and liquids, removal of contaminants, and further chemical processing. An important step in high-BTU gasification is methanation, where the ratio of methane gas to other gases (usually carbon dioxide) is increased through a catalytic reaction until synthetic gas of pipeline quality (1000 BTU per cubic foot) is produced. In many coal conversion processes, this stage of refining the raw product gas into final products can involve a large number of highly interrelated physical and chemical operations.

Process Inputs

In addition to coal, many conversion processes require large quantities of hydrogen, oxygen, or steam as resource inputs. Because the quantities are so large, these inputs are usually generated in an auxiliary stage of the coal conversion process. Spent char (a partially burned form of coal) from the conversion reactor is often used to produce either steam or hydrogen. Hydrogen can be produced from the char by gasification; steam can be produced by using the char to fire a boiler. Oxygen is usually produced through a separate process.

Efficiency

The thermal efficiency\(^1\) of the commercially available coal conversion processes is reasonably high — ranging from 60 percent for

\(^1\) Thermal efficiency is measured by the BTU heating value of the synthetic fuel produced as a proportion of the BTU heating value of the input coal.
the Koppers-Totzek process to 72 percent for the Lurgi process. Expectations are that the new conversion processes currently being developed will not yield thermal efficiencies that are much more than 10 percent higher.

TECHNICAL PROBLEMS

Because of past research and the wealth of operating experience with existing processes, the basic chemistry of coal conversion is reasonably well established.\(^1\) The new conversion processes are based on chemical reactions that are slightly different from existing processes and will operate at substantially higher pressures and temperatures. These differences entail new technical problems, but there is no great uncertainty that technical solutions can be found. But because of the potential increases in conversion efficiency expected with the new processes over existing processes are so small, it is critical that these technical solutions do not degrade overall performance so much that improvements in efficiency are more than offset by increased costs.

For gasification processes, the main technical problems are:\(^2\)

- Plugging of the gasifier by slag and ash produced during gasification.
- Removing particulates from the raw product gas at high temperature.
- Removing acid gases from the raw product gas.


--\(^2\) Federal Energy Administration, pp. 22-26; Ad hoc Panel on Coal Gasification, p. 43.
K-11

- Reducing corrosion and fluxing in the reactor vessel through the development of new materials and mechanical designs.
- Reducing the cost and increasing the reliability of methanation processes.¹

For liquefaction, the main technical problems are:

- Improving methods of separating solids from liquids so that less steam is required.
- Improving the temperature stability, resistance to sulphur corrosion lifetime, and selectivity of catalysts used and reducing their costs.
- Developing containment materials that are less susceptible to degradation from sulphur compounds and yet still have good mechanical properties over wide temperature and pressure ranges.

Liquefaction and gasification processes have some common technical problems:

- Improving equipment for injecting coal into pressurized systems.
- Developing efficient systems for transporting and injecting hot char.
- Developing improved high capacity pumps and valves suitable for operation with hot solids or gases (these items do not exist for the conditions of service required).
- Decreasing the sensitivity of the conversion process to coal composition.

This last area is important because the composition of coal from different locations across the country varies widely: in their BTU

¹Developing an improved methanation process is probably the most difficult technical problem in gasification.
content, combustibility, water content, coking properties, and so forth. If coal conversion processes are efficient with only certain classes of coal, the problem of advancing coal conversion technology into commercial usage becomes far more complex. A different type of process might have to be developed for each type of coal.

NEEDS FOR COST INFORMATION

Because of the tremendous costs involved in building large energy facilities, there is great need for good cost information on various synthetic fuels processes.

Cost Factors

For a specific plant to be built at a certain location and owned by a given firm or public organization, the costs of a coal conversion process can be quickly broken down into a large number of factors that must be considered. A partial list includes:

Capital costs:
- Machinery and equipment purchase cost
- Construction costs and design fees
- Working capital for construction and operation
- Interest rates on debt
- Return on equity required
- Ratio of debt to equity financing
- Income tax rate
- Depreciation schedule

Operating costs:
- Coal amount and price
- Water amount and price
- Electric power amount and price
- Labor amounts and rates
- Catalyst and chemical amounts and prices
Credit prices for byproduct chemicals
Spare parts inventory and replacement
Stream factor (operating hours per year)

It is important to recognize for purposes of assessing the value of demonstrations, that only a portion of these cost factors are directly related to conversion technology. The factors specific to the conversion technology include the specific items of equipment required, the amount of resource inputs required (such as coal, water, and labor), and the stream factor, and so forth. All the other factors, such as machinery and equipment prices, financial rates, and prices of resource inputs are exogenous to the technology. Although a detailed cost analysis is required, indications are that the sensitivity of costs to these exogenous factors is substantially greater than to the technology related factors.

Cost Estimates

The projected capital costs of coal conversion plants currently being considered are high. For example, a high-BTU gasification plant capable of producing 250 million cubic feet of gas per day is estimated to cost between $500 million and $1 billion.

Although there are few comprehensive analyses, a common assumption is that synthetic fuels plants need to be large to take advantage of economies of scale. Expectations are that costs per unit of fuel produced decline for plant sizes up to and maybe beyond the figure of 250 million cu. ft. per day indicated above. But as plant sizes increase, more of the plant product will usually have to be shipped long distances. Consequently, gains in production efficiency will be increasingly offset by transportation costs.

Current estimates of the costs of producing synthetic fuels from coal are highly uncertain. Estimates by the Synthetic Fuels Task Force of Project Independence\(^1\) are in the neighborhood of $2.00 to $3.00 per million BTU, while estimates by the Synfuels Interagency Task Force of the President's Energy Resources Council,\(^2\) are in the neighborhood of $3.00 to

\(^{1}\) Federal Energy Administration, p. 37.
$5.00 per million BTU. These estimates are shown in Figs. 6, 7, 8, and Table 1. Importantly, it is expected that the learning curve for synthetic fuels may be steep, which could narrow the price gap between the costs of synthetic and natural fuels over the long run. An estimate of the learning curve for synthetic fuels is shown in Fig. 8.

In comparison to these cost estimates for synthetic fuels, natural gas is currently selling for $1.25 per million BTU in unregulated, intra-state markets. Petroleum is currently selling for approximately $2.00 per million BTU or $11.00 per barrel.

EXTERNALITIES

There are four major externalities of synthetic fuels technology. The first concerns the large amounts of water required and the scarcity of water in the West, where much of the coal supply is located. The second concerns strip mining operations. Another concerns the effluent output of synthetic fuels plants, including large amounts of sulphur and ash. Finally, there are important questions concerning the impact of synthetic fuels plant construction and operations on community development.

![Graph showing synthetic fuels cost (9% Utility Financing)](image-url)

Fig. 6--Synthetic Fuels Cost (9% Utility Financing)
Fig. 7—Synthetic Fuels Cost (15% Discounted Cash Flow)


Fig. 8—Prices of Liquid and Gaseous Fuels
Table 1
SYNTHETIC FUELS COSTS ASSUMING CURRENTLY PROPOSED TECHNOLOGIES AND DEREGULATION OF NATURAL GAS

<table>
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<th>Price required to yield rate of return of: (^{a,b})</th>
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<tbody>
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<td>High BTU Gas, $/million BTU(^c) Unregulated case</td>
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<td>Fuels derived from Biomass, $/million BTU Unregulated case</td>
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<td>Utility/industrial, $/million BTU(^d) Unregulated case</td>
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<td>Syncrude, $/barrel(^d) Unregulated case</td>
<td>18.50-22.00</td>
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<tr>
<td>Shale oil, $/barrel Unregulated case</td>
<td>10.00</td>
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\(^a\) Regulated rate of return based on undiscounted return on equity after taxes assuming 75 percent debt and 25 percent equity.

\(^b\) Unregulated rate of return based on discounted cash flow after taxes on entire capitalization.

\(^c\) Range represents coal cost of $5 or $9 per ton (Western coal).

\(^d\) Range represents coal cost of $11 or $17 per ton (Eastern coal).
in remote areas and how to minimize the social problems associated with creating new communities to accommodate a large influx of new labor and supporting industries.

Water

Although the amount of water needed in a synthetic fuels plant varies considerably with the water content of the coal used and process characteristics, most synthetic fuels plants of the sizes discussed above will require roughly 10,000 acre-feet of water per year, which may be difficult to obtain in certain areas of the West where most of the available water has already been allocated to other uses. Owners of synthetic fuels plants will have to compete with other water users for licenses to available water supplies.

Water supply requirements have implications for the siting of synthetic fuels plants because, in addition to being located near a coal field and a pipeline, a plant must also be located near a large and reliable source of water to minimize costs. A quotation from a report on the feasibility of building a gasification plant in the lignite fields of southwestern South Dakota illustrates the problem.¹

¹Consolidation Coal Company, "Pipeline Gas from Lignite," NTIS, #PB 166817, January 1965.
The southwestern counties of North Dakota, and Harding in South Dakota (where the coal is located) must rely on the Little Missouri River to supply water to a gasification plant. However, the flow in this river is quite erratic and, to quote Mr. Charles L. Hipp, Chief Engineering Division, U.S. Army Engineers District, Omaha, 'Zero flows of extended duration occur in most years of record.' The average daily discharge of the Little Missouri River at a gaging station at Camp Crook, South Dakota was 131 cu. ft. per second.

Gasification plants located at the southwestern part of North Dakota and the northwestern section of South Dakota will therefore depend for their water supply, not only on the Little Missouri River, but also on any available underground wells that can be developed and, also, on impounded water in a local dam. This more complex water supply problem will add some additional cost to the production of pipeline gas and will be an important factor in plant site location.

Strip Mining

The large amounts of coal required for a synthetic fuels plant will have to be obtained from strip mines, and most of these will be new mines in previously undeveloped areas. The environmental effects of these strip mines are an externality of synthetic fuels technology and a source of uncertainty with regard to its future. The uncertainties are the reactions of local communities and the extent to which strip mining regulations will be changed in the future. Little can be done technologically to reduce these uncertainties; they will have to be worked out through the political process.

Recent research on the nuclear power industry suggests that cost implications of these uncertainties may be substantial. The principal finding is that delay in reactor licensing is one of the most significant factors in explaining the rate at which the costs of building nuclear power stations have increased over the past several years.

The problem...is not administrative or technical in the sense that a somehow inefficient set of regulatory machinery has caused artificial cost increases. Rather, the regulatory process has been used as a device to give effect to the view that reactor technology is not as valuable to society as the plants implied. The process by which opponents of nuclear
power are trying to establish their views about the ultimate value of nuclear power to society is causing delays and costs which obviously can only be reduced by a reduction in the level of the controversy itself.\(^1\)

While atomic power raises images of danger to society that are not in inherent in synthetic fuels technology, large-scale uprooting of the land may be no less a matter of controversy. Sizeable areas of Illinois, North Dakota, Wyoming, and Montana rest on a thick bed of strip-mineable coal.\(^3\)

Waste Products

Synthetic fuels plants will produce large quantities of ash and sulphur that will have to be disposed of. For plants of the size discussed above there will be more than 6500 tons per day of ash and several hundred tons of sulphur, depending on the sulphur content of the coal. The ash can be returned to the coal mine, but there are many unresolved questions about what chemicals the ash will contain and possibilities of hazardous leaking (arsenic is one of the likely components). In the short run, sulphur can be sold as a useful chemical, but if large numbers of synthetic fuels plants are built, the quantities produced may far exceed what can be sold.

Many other atmospheric, liquid, and solid wastes will be produced by synthetic fuels plants but not in as large quantities. Even so, costly pollution control measures will be required. The costs of these measures are as yet unknown because the amounts and types of these wastes will vary with the conversion process and the coal. As pointed out in the Project Independence report:

Because no large-scale plants have ever been constructed and operated, the potential environment impact (of synthetic fuels technology) is not fully-defined; it is clear, however, that land, water, and atmospheric wastes will be involved, and that all these areas will require control and abatement measures.\(^2\)

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\(^2\)Federal Energy Administration, p. xxi.

Social and Economic Effects

Not much is known either about the social and economic effects on communities and regions where synthetic fuels plants are located. The results of the few studies that have been done on the effects of locating large industries in small communities are inconclusive, except that the expected influx of service industries, strains on public services, and urbanization have been observed. The effects of synthetic fuels plants may be greater because of the size of these plants in relation to the plants that have been studied and the probability that they will be reliable sources of low-cost energy in an energy-short economy, which will be an attraction to other industries. What the reaction of communities and states will be to these intrusions is unclear. Some communities, and especially states, may welcome the economic and social changes, while others may not. In many cases, their reactions will be highly political and may involve lobbying either for or against the location of synthetic fuels plants within their territories.
II. SYNTHETIC FUELS TECHNOLOGY DELIVERY SYSTEM

Because synthetic fuels are not currently being used in the United States on a large scale, there is no synthetic fuels technology delivery system. Use of the new technology being developed by the Coal Conversion Division will require a whole new industry of producers, suppliers, and engineering organizations, and that will happen only if the demand for synthetic fuels is sufficient, the regulatory environment is favorable, and there are no other institutional barriers.

The eventual size of this industry will depend on economic and other factors, but, assuming that synthetic fuels plants of the size discussed above are built, 50 percent of total gas production in 1973 could be supplied with approximately 50 gasification plants or 60 liquefaction plants.¹ These 60 liquefaction plants would also supply 20 percent of total liquid fuel production in 1973.

DEMAND

Because the fuels produced by coal conversion are perfect substitutes for fuels already on the market, the demand for synthetic fuels will be much the same as the demand for fuels from other sources. As mentioned previously, synthetic fuels cannot currently be profitably priced close to the market. But, if the costs of synthetic fuels production decline substantially, and the market prices of crude oil and natural gas increase enough, an enormous market for synthetic fuels can be expected to open up. However, how large this market will be how soon is uncertain. Two obvious sources of uncertainty are future oil and gas prices and the steepness of the learning curve regarding costs of synthetic fuels production.

Environmental Regulations

Another source of uncertainty is related to the fact that synthetic fuels are inherently low in sulphur content. Because sulphur must be removed from the raw product stream in a synthetic fuels process to avoid corrosion and

¹Liquefaction plants of 39,000 barrels per day and 225 million cu. ft. of gas per day, or gasification plants of 250 million cu. ft. of gas per day.
contamination problems in the cleanup stages, the final products are low in sulphur content, even if high sulphur coal is used. Therefore, as environmental regulations are tightened or relaxed, the demand for low sulphur fuels relative to other fuels correspondingly increases or decreases. Because there is a shortage of low sulphur fuels from natural sources, the effect of environmental regulations will be to increase the prices that can be charged for synthetic fuels relative to other fuels. However, since there is uncertainty about future environmental regulations, there is a corresponding uncertainty about what the demand for synthetic fuels will be.

PRODUCTION

The range of possible types of firms that may decide to buy synthetic fuels plants is very broad:

- **Natural gas pipeline companies** may purchase high-BTU gasification plants.
- **Utilities** may purchase low-BTU gasification plants and site them with an electrical power generation facility.
- **Oil companies** may purchase either gasification or liquefaction plants.
- **Petrochemical companies** may purchase liquefaction plants.
- **Other manufacturing firms** having high energy requirements may purchase gasification plants for their own use.
- **Other firms** not previously in the energy business may decide to go into it.

Petrochemical companies and manufacturing firms may be the first to purchase synthetic fuels plants because of their need for reliable energy supplies.\(^1\)

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\(^1\)U.S. Congress, House of Representatives, hearings on Special Energy Research and Development Appropriations for 1975, House Committee on Appropriations, 93rd Congress, 2nd Session, 1974, testimony of Dr. Gouse, Acting Director, Office of Coal Research.
The stakes in the game among these producers of deciding which technology to invest in are extremely high—higher than with any of the other technologies examined in this study of technology demonstrations. Not only are large amounts of money involved but, depending on which firms are successful, ownership of the energy economy may be substantially re-distributed. For example, the distribution of ownership will be quite different if pipeline companies own a large number of high-BTU gasification plants than if oil companies own a large number of liquefaction plants. Because of this, synthetic fuels demonstration programs will undoubtedly be conducted in an intense and highly political environment.

Regulation

The primary source of uncertainty for potential purchasers of synthetic fuels plants is price regulation by the Federal Power Commission and the Federal Energy Administration. The more fuels prices are held below market prices, or there is uncertainty that regulations will be flexible enough to allow cost increases to be passed on to consumers, the less various potential producers will be willing to purchase synthetic fuels plants.

Competing Technologies

Another source of uncertainty facing producers in deciding to purchase a synthetic fuels plant is that there are a large number of technologies on the horizon, some of which may prove to be lower cost than synthetic fuels technology. Firms have to decide whether to invest in a synthetic fuels plant now and hope that a much lower cost technology does not emerge over its 20- to 30-year lifetime, or wait until the cost picture clears. Some technologies at nearly the same stage of development as synthetic fuels include:

- in situ coal gasification (gasification of coal while it is still in the ground)
- advanced systems for the direct combustion of coal
- oil shale conversion
- piping of slurried coal

Less developed technologies include coal-fed magneto hydrodynamic systems and solar power.

**World Oil Prices**

Another source of uncertainty is the monopoly power of the OPEC\(^1\) cartel to set world oil prices. Should OPEC decide to cut oil prices in the future to discourage the development of alternative energy sources and thereby retain their market power, the bottom could fall out of the market for synthetic fuels, leaving synthetic fuels producers in a difficult position. Although some believe that OPEC is unlikely to cut prices, the probability is certainly not zero. The oil and gas industries are currently lobbying Congress to pass a price support program on the basis that they cannot afford the risk of investing billions of dollars in new energy technologies when there is the possibility of a precipitous decline in world oil prices.

\(^1\) Organization of Petroleum Exporting Countries.
Labor

Producers will also have to face labor union issues. Coal conversion plants will require between 200 and 1000 workers, depending on the degree of plant automation and other factors. The degree of automation is one kind of issue that will have to be negotiated with labor unions, and the outcomes could have significant implications for the costs of synthetic fuels plants. One estimate is that with high automation and minimum labor, labor costs will be approximately 10 percent of total operating costs including coal purchase.\(^1\) Another set of issues concerns which unions will have what jurisdictions in synthetic fuels plants. The main contenders are the United Mine Workers (UMW) and the Chemical Workers of America (CWA). The possibilities of serious conflicts are high because the UMW is an independent union and the CWA is aligned with the AFL/CIO.

Financing

Perhaps the most difficult problem facing producers will be obtaining the large amounts of capital required to construct synthetic fuels plants. The amounts are so large that it will be necessary to obtain loans or equity financing. Both banks and all other potential investors will be at least as sensitive to all the uncertainties surrounding synthetic fuels as the producers.

\(^1\)Federal Energy Administration, p. 34.
EQUIPMENT SUPPLIERS

The suppliers of equipment for synthetic fuels plants are likely to
be the same ones that serve the oil refining industry. The critical
components in synthetic fuels plants will be the reactor vessels and
large pumps, pipes, and valves, which will be similar to the distillation
towers, cracking units, and pipes and valves used in petroleum refining.

The performance requirements are different enough in synthetic fuels
that investment will be required in the development of new components
sufficient in size and performance reliability to meet the special
operating conditions in synthetic fuels plants. Unless equipment
suppliers see a large enough market in these components to warrant the
investment of their own funds, or the government directly supports the
necessary R&D, these necessary parts will not be available for either
demonstration or commercial plants.

Testimony in Congress by a Coal Conversion Division official\(^1\) illus-
trates the problem:

Many of the problems we are running into right now in
pilot plants\(^2\) are due to the fact that these component parts,
like pumps, valves, and so on, were not specifically designed
for the unique duty we are using them for.

Equipment development ... is an extremely important part
[of our demonstration program]. We are trying to accelerate
efforts on this, working with manufacturers of specific types
of equipment, filters, valves, and the like. This calls for
the Government's participation. We can't get the manufacturers
to spend millions of dollars on designing the unique slide
valve for special duty unless they are absolutely convinced
that this technology will go forward. For this reason we
are providing encouragement for them.

\(^1\) U.S. Congress, Hearings, p. 691.
\(^2\) Pilot plants are large-scale laboratory facilities for testing
synthetic fuels processes prior to conducting a demonstration. See
Section IV.
There could be ancillary utilization of these items of hardware but at this time it is not possible to predict with any degree of accuracy what the market for these would be.

Thus, an important barrier to the utilization of synthetic fuels technology could be the unavailability of needed mechanical equipment.

Another barrier to the emergence of a synthetic fuels industry is that there are problems in designing and manufacturing the large reactor vessels needed in commercially sized plants. The primary constraints are that:

1. There is a serious shortage of steel for the fabrication of ... energy [facilities]. Steel resources at present are being taxed to virtually their limit by existing demands. The imposition of additional requirements may necessitate the establishment of national priorities. The continued expansion of the nuclear industry (a large steel user) precludes the possibility of large-scale plant capacity development of coal gasification plants unless additional steel plant capacity is made available....

2. For some coal gasification systems the design parameters of diameter, length, operating pressure, and operating temperature require the fabrication of reactor vessels [that] may be beyond ... existing technology.

3. Current heavy-walled pressure vessel technology is primarily based on shop fabrication, either of total systems or major components. Transportation restrictions on the movement of very large heavy-walled pressure vessels [needed in synthetic fuels plants] ... dictates that these vessels be field erected and fabricated. The necessary field erection/fabrication technology is not proven for the large reactor vessels under consideration.

4. Appropriate and adequate field fabrication techniques and equipment will have to be developed before ... quality vessels can be field-fabricated economically.

5. Consideration will have to be given to the allocation of critical alloying elements, such as nickel, chromium, molybdenum, etc., to meet ... many ... vessel requirements for alloy(s) and stainless steel.

---

1 Federal Energy Administration, p. 63.
Furthermore, there may be severe limits on fabrication capacity:1

The principal heavy pressure vessel manufacturers are: (1) Babcock & Wilcox (B&W), (2) Combustion Engineering, (3) Westinghouse, (4) American Bridge, Division of U.S. Steel, (5) Bethlehem Steel, (6) Chicago Bridge & Iron, (7) C. F. Braun, (8) Wyatt Corporation, and (9) Foster Wheeler. Many of these organizations currently are fully committed to the fabrication of pressure vessels for commercial nuclear power generation. As such, they are the principal users of heavy plate in the United States. Virtually all are fully booked for the next 5 to 6 years. For example, B&W is currently fabricating for 1977 delivery with bookings to 1980. The Barberton facility of B&W has a capacity of 15 heavy-wall vessels (steel drum type) per year. Typically, these vessels are 70 to 80 inches ID, 6 to 8 inches wall thickness, and 100 feet long, fabricated of carbon, manganese (SA299) type steels. B&W has experience and capabilities to fabricate low-alloy and stainless steel pressure vessels of equivalent size.

The typical size of reactors for synthetic fuels plants will be 170 feet high, 25 feet in diameter, with walls 12 inches thick.

COAL MINING

The large supplies of coal that will be needed for synthetic fuels plants will require opening many new coal mines. In many cases, these mines will be collocated with a synthetic fuels plant in order to minimize coal transportation costs, and long-term contracts will have to be written with mine owners to guarantee coal supplies. Each plant of the size discussed above will require 3 to 12 million tons of coal per year, depending on the process used, which is approximately equal to 1973 production levels in the West or 1.6 percent of total U.S. coal production in 1973. Fifty of these plants would require an 80 percent expansion of coal mining capacity over that in 1973.

1Ibid., p. 66.
Joint Partnerships

Collocation of synthetic fuels plants with dedicated coal fields raises critical questions of the institutional relationships between the owners of these dedicated mines and the owners of the fuels plants. Long term contracts are common in the coal industry today with steel mills and utilities; but in most of these cases, coal is shipped to the consuming plant site, making it possible for these plants to switch to other suppliers when contracts come up for renegotiation (most contracts are renegotiated after every mine signs a contract with the UMW). Synthetic fuels plants collocated with mines will have only the expensive alternative of buying coal elsewhere and shipping it in.

Although all the aspects of the partnerships that will have to be worked out between coal mine and synthetic fuels plant owners are not clear, a critical one will be the mechanism for agreeing on a price for coal. A complication will be that the organizational styles of the fuels plant and the coal mine owners may be quite different, depending on who the fuels plant owners turn out to be. Some plant owners are likely to be from industries that are more technologically oriented and have higher profit margins (e.g., oil companies) than coal companies have traditionally had.

Equipment Supply

The critical problems in expanding coal production would be the ability of coal companies to raise the necessary capital and the capacity of equipment companies to supply the large draglines (coal stripping machines) that each mine would require. A recent study of equipment company capacity indicates that there are at present only three companies capable of building draglines of sufficient size, the capacity of the two largest of these companies is approximately 10 units per year, and they are "sold out" up to 1980. Three to four draglines are needed for each mine producing 10 million tons of coal per year, the approximate amount needed for a 250 million cu. ft./day synthetic fuels plant.

1 Many coal companies are now owned by oil companies.
ENGINEERING DESIGN AND CONSTRUCTION FIRMS

A fourth component of the synthetic fuels technology delivery system will be engineering design and construction firms with the technical and managerial capacity to construct synthetic fuels plants. The Project Independence Report estimates that existing firms serving other industries will be able to supply all the service needed, although this will depend on whether or not these industries do not also need to expand their plant capacity in the future.¹

PROCESS R&D

The synthetic fuels industry will also need organizations capable of continuing with R&D on synthetic fuels processes and working with construction and engineering firms on plant design. Each synthetic fuels plant will be designed to process a certain kind of coal, deliver different products, meet different environmental and water restrictions, and so forth. In atomic energy this R&D capability exists in such large firms as General Electric and Westinghouse, whereas in oil refining it is in the producing sector (i.e., the oil companies). For synthetic fuels, few of the potential producers except oil companies have any R&D capabilities. The firms that are conducting demonstration projects for the Coal Conversion Division are a potential source of this R&D capability, but all of these firms are small and have little corporate backing. Other than with direct support from the federal government, it is unclear where these firms will obtain enough revenues to become large and stable organizations. Revenues from patents granted on R&D performed for the government is one possible source of this income, but ERDA policy is for the government to hold all patent rights.

It is important to recognize that synthetic fuels plant design will not be a turnkey business, although as experience is gained plant designs will probably converge to some optimum configurations. Process improvements will continue to be possible for a long time, and each plant will have to be tailored to its site. For example, the water content of the coal will affect water needs, the sulphur content will affect needed capacity for sulphur removal, and so forth.

¹Federal Energy Administration, p. 71.
III. THE COAL CONVERSION DIVISION'S SYNTHETIC FUELS PROGRAM

The Coal Conversion Division of ERDA is the main federal office involved in the development of new synthetic fuels processes. Their overall objective is to develop synthetic fuels processes rapidly enough that three trillion cubic feet of synthetic gas will be being produced annually by 1985.\textsuperscript{1} This would require approximately 30 plants of the size discussed above.

HISTORY AND BUDGET

The Coal Conversion Division was created in 1974 as part of a large reorganization of federal agencies involved in energy R&D into the Energy Research and Development Administration. The Coal Conversion Division was transferred from the Department of the Interior, where it was called the Office of Coal Research (OCR).

OCR was established in 1961 by the Coal Research Act, which provided a broad charter to conduct research on "new and more efficient methods of mining, preparing, and utilizing coal" (30 U.S.C. 662). However, as Table 2 illustrates, funding was limited, and permitted only low level research on liquefaction and gasification processes. OCR's budget did not begin to grow substantially until after the oil embargo in 1974. The current budget is over $200 million, a five-fold increase over 1973.

Early OCR work on coal liquefaction resulted in three pilot plants, including the Project Gasoline plant in Cresap, West Virginia; the COED process pilot plant at Princeton, New Jersey; and the Solvent Refined Coal pilot plant in Fort Lewis, Washington. In gasification, OCR bolstered its small funding by pursuing technologies that had been developed privately. For example, the Institute of Gas Technology had been

\textsuperscript{1}"Shaping Coal's Future Through Technology," Office of Coal Research, 1974-1975, p. 2.
### Table 2
**APPROPRIATIONS FOR OFFICE OF COAL RESEARCH, FY 1961 - FY 1975**

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<th>Fiscal Year</th>
<th>Appropriations (millions)</th>
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<td>1961</td>
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<td>123.4</td>
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<tr>
<td>1975</td>
<td>261.3</td>
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investigating the HYGAS process since 1946; OCR began supporting this research in 1964, resulting in a HYGAS pilot plant that began operations in Chicago in 1971. Similarly, in 1964, OCR began funding the CO₂ Acceptor process originally developed by the Consolidation Coal Company; this too was used in a pilot plant operation starting in 1971. The BIGAS process is another major high-BTU gasification technology now being explored by OCR. It was developed by Bituminous Coal Research, Inc., in the early 1960s; a pilot plant is now under construction in Homer City, Pennsylvania. Finally, the Agglomerating Burner process was developed and patented by Union Carbide and is now being partially
supported with OCR funding. A complete list of current Coal Conversion Division projects is shown in Table 3.

ORGANIZATION OF R&D EFFORT

The Coal Conversion Division's synthetic fuels program is organized around four main kinds of R&D activities:

- Process development
- R&D on process components
- Pioneer plants
- Systems design and evaluation studies

The COED, HYGAS, and BIGAS efforts are examples of process development activities, which involve the design and development of an entire synthetic fuels process, including the pretreatment through cleanup stages, and starting from research and continuing through demonstration. R&D on process components involves design, development, and testing work on one part or aspect of a synthetic fuels process. For example, R&D on process components includes the development of a process for converting char to hydrogen (see Fig. 4). Pioneer plants are a new category of projects that the Coal Conversion Division is planning to support. They will involve experimentation in commercial plants with new components for synthetic fuels processes. In addition to all these types of projects, system design and evaluation studies are supported to obtain information on the performance of systems being developed and to plan future Coal Conversion Division activities.

Process Development Model

As indicated in Table 3, the bulk of the Coal Conversion Division's funding has been for process development. Process development occurs through a series of four stages that the Division has established: Bench-scale Research, Process Development Unit, Pilot Plant, and Demonstration Plant. Tables 4 and 5 describe these stages in detail. An official in the Coal Conversion Division emphasizes that this particular
<table>
<thead>
<tr>
<th>Project</th>
<th>Performer</th>
<th>Co-sponsor</th>
<th>Budget (millions)</th>
<th>Coal Conv. Div.</th>
<th>Co-sponsor</th>
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<td>Solvent refined coal</td>
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<td>Advanced coal gasification system</td>
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<td>Low-BTU fuel gas</td>
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<td>Characterization of liquid fuels from coal</td>
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</tr>
<tr>
<td>Twenty-five foot, high pressure fixed bed gas producer</td>
<td>McDowell Wellman Engineering</td>
<td>--</td>
<td>$.10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


*The Coal Conversion Division is also supporting many R&D projects on advanced direct combustion systems and magnetohydrodynamics, which are not included.*
<table>
<thead>
<tr>
<th>Stage of Development</th>
<th>Plant Characteristics</th>
<th>Reactor Characteristics</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bench-scale Research</td>
<td>Laboratory simulation of conversion stage only.</td>
<td>Conversion reactor vessel inches in diameter and a few feet high.</td>
<td>Hundreds of thousands of dollars</td>
</tr>
<tr>
<td></td>
<td>All resource inputs exogenously supplied.</td>
<td>One to ten lbs. of coal per hour processed.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Batch processing. Runs last for hours to days.</td>
<td></td>
</tr>
<tr>
<td>Process Development Unit</td>
<td>Laboratory simulation of conversion and product cleanup stages.</td>
<td>Conversion reactor vessel about a foot in diameter and several feet high.</td>
<td>Millions of dollars</td>
</tr>
<tr>
<td>(PDU)</td>
<td>All resource inputs still exogenously supplied</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Some feedback loops closed, but all process steps are physically separated to facilitate design changes and breaking of feedback loops.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Configuration of PDU approximates configuration of operational plant.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot Plant</td>
<td>Small-scale prototype of operational plant.</td>
<td>Conversion reactor vessel several feet in diameter and several tens of feet high.</td>
<td>Tens of millions of dollars</td>
</tr>
<tr>
<td></td>
<td>Some steps in conversion process integrated to improve performance.</td>
<td>Tens of tons of coal processed per hour.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All other steps are modularized to allow maximum flexibility for interchanging and modifying parts.</td>
<td>Semi-continuous operation. Runs last for days to several weeks.</td>
<td></td>
</tr>
<tr>
<td>Stage of Development</td>
<td>Plant Characteristics</td>
<td>Reactor Characteristics</td>
<td>Cost</td>
</tr>
<tr>
<td>----------------------</td>
<td>---------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Demonstration</td>
<td>Fully instrumented to allow measurement of all potentially important process variables.</td>
<td>Conversion reactor vessel tens of feet in diameter and about one hundred and fifty feet high.</td>
<td>Hundreds of millions of dollars.</td>
</tr>
<tr>
<td></td>
<td>Full-scale prototype of an operational plant.</td>
<td>Thousand of tons of coal per hour processed.</td>
<td>Continuous operation.</td>
</tr>
<tr>
<td></td>
<td>All steps as fully integrated as technically advantageous.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Components overdesigned to minimize probability of breakdown.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Overinstrumented compared with commercial plant to allow assessment of performance and determination of minimum cost plant design.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Equipment for controlling and abating waste effluents included.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Product delivered to a commercial user.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R&amp;D Areas</td>
<td>Bench-scale Research</td>
<td>Process Development Unit</td>
<td>Pilot Plant</td>
</tr>
<tr>
<td>---------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Measure kinds and amounts of products in converter output.</td>
<td>Develop methods for separating out the various products in the converter output.</td>
<td>Assess sensitivity of material balances in the process to changes in process parameters.</td>
</tr>
<tr>
<td></td>
<td>Measure sensitivity to converter parameters.</td>
<td>Assess sensitivity of material balances in the process to changes in process parameters.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Assess areas of technical uncertainty and needs for research.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scale-up problems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste effluent production</td>
<td>Measure waste effluents in converter output.</td>
<td>Assess and solve technical problems due to scale-up.</td>
<td>Assess and solve technical problems due to scale-up.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measure waste effluents from all steps in the process.</td>
<td>Measure waste effluents from all steps in the process.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Assess sensitivity of waste effluent production to process parameters.</td>
<td>Minimize waste effluent production through process design changes.</td>
</tr>
<tr>
<td>Sensitivity to coal type</td>
<td></td>
<td>Assess sensitivity to coal type.</td>
<td>Assess sensitivity to coal type.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Redesign to reduce sensitivity to coal type.</td>
<td></td>
</tr>
<tr>
<td>R&amp;D Areas</td>
<td>Bench-scale Research</td>
<td>Process Development Unit</td>
<td>Pilot Plant</td>
</tr>
<tr>
<td>------------</td>
<td>----------------------</td>
<td>--------------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Corrosion and wear</td>
<td>Assess likely corrosion and wear trouble spots.</td>
<td>Assess and solve corrosion and wear problems (may involve development of new materials and components, or process redesign).</td>
<td>Assess and solve corrosion and wear problems (may involve development of new materials and components).</td>
</tr>
<tr>
<td>Reliability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Estimate process economics (mainly resource inputs required and capital cost).</td>
<td>Estimate process economics for different plant configurations.</td>
<td>Estimate process economics for different plant configurations.</td>
</tr>
</tbody>
</table>

Table 5 (cont.)
sequence of stages is traditional in the process engineering profession but may not be optimum for developing other kinds of technologies. He specifically cites electric power plant development as an exception. There are differences among the stages in both the physical characteristics of the plant constructed and development objectives.

The most obvious physical difference is in the size of the reactor vessel in the converter stage. In bench-scale research, the reactor vessel is only a few inches in diameter and a few feet high. In each subsequent stage, the reactor vessel is incrementally increased in size until in the demonstration plant it is tens of feet in diameter and about 150 feet tall. Other physical differences are in the plant configuration. In the early stages, steps in the conversion process are all physically separated and highly instrumented to allow maximum flexibility to interchange parts, direct control of parameters in each step of the process, and experiments with alternative arrangements of product flows. In the later stages they may be more highly integrated and less totally instrumented.

The development objective in bench-scale research is mainly to prove the technical feasibility of a new method for converting coal to synthetic fuels -- does the process work as intended? In the PDU stage, basic decisions are made regarding which products in the converter output will be maximized. These decisions are basic because in the pilot and demonstration stages, little flexibility remains to alter the balance among products in the process output. The Coal Conversion Division does not impose product objectives on the design teams; as a result, the processes that are currently being developed differ substantially with regard to the ratios of products produced. This is particularly true among liquefaction processes. The Division could impose product objectives by specifying a set of relative weights in making process output decisions. This would simplify cost comparison of different processes and federal decisionmaking with regard to which processes should be demonstrated, but it might prevent process development teams from taking advantage of some technological opportunities.

A principal reason for conducting process development in stages is to deal with "scale-up" problems. Examples of scale-up problems are
instabilities in reactor combustion zones and plugging of process components. By increasing the plant size in increments, the number of scale-up problems that must be dealt with at each stage is smaller, and knowledge of ways to solve these problems can be gained less expensively than if large increases in plant size are made from stage to stage. Knowledge concerning ways of solving scale-up problems obtained at one stage can be used to advantage in designing the plant for the next stage. Scale-up problems can occur each time the plant size is increased and even in the demonstration plant. For example, the project team developing the HYGAS process expects that when a demonstration plant is built there may be a different amount of back mixing in the reactor that would result in a different level of oxygen consumption than predicted by straight extrapolation of data from the pilot plant. If back mixing increases and a way cannot be found to reduce it, the operating cost of the HYGAS process would increase because oxygen is expensive to supply.

Close attention is not paid to improving plant reliability until the pilot and demonstration stages of development. At the pilot plant stage, corrosion and wear problems can be detected and efforts directed to modifying process parameters, or developing new materials and components, but reliability is not actually tested until the demonstration stage when, for the first time, the plant is operated continuously. However, even after demonstration plant operations, reliability will not be accurately known because the demonstration plant will be overdesigned to minimize the possibility of breakdown. During the demonstration runs, measurements will be taken to determine the minimum component sizes needed in a commercial plant for reliable operation, but actual experience with commercial operations plants will be needed to accurately determine reliability.

The demonstration plant is also the principal stage where cost uncertainties will be determined. Because the demonstration plant will be overdesigned for reliable operation, as well as overinstrumented to allow detailed measurement of process parameters, its cost will necessarily be higher than that of a commercial plant. Thus, the cost of the demonstration plant will only be indicative of the cost of a
commercial plant. However, design studies will be conducted on the demonstration plant to obtain estimates of plant capital and operating costs that will be more accurate than at the end of previous stages.

The demonstration plant is also where final measurements of waste effluents are made and the cost effectiveness of control and abatement procedures determined. Effluent production is considered as early as the bench-scale and PDU stages, but not until the pilot plant stage are efforts made to reduce waste products through changing the process design and developing control and abatement procedures. Actual waste effluent production can not be accurately predicted until measurements are taken on the demonstration plant.

The work force will be larger in the demonstration plant than in a commercial plant because of needs to collect data and make system modifications. In all probability, most of this work force will be unionized, which will establish precedents for any commercial plants built.

Cost Sharing

As indicated in Table 2, part of the costs of most of the Coal Conversion Division's process development projects are paid by industry. In most cases, the industry share is one third of the total cost.

Size of the Demonstration Plants

One issue is how large the demonstration plants should be. The two alternatives are to construct "semi-works" sized or "full-scale" demonstrations. In a full-scale demonstration, the plant would be constructed at commercial scale but would include only one train of the conversion process rather than the three or four trains in parallel that would be required for a commercial plant. To facilitate conversion of the demonstration to a commercial plant, the land area purchased and the plant utilities constructed for the demonstration would be large enough that a commercial plant could be built after the demonstration simply by adding two or more trains of the conversion process. In the semi-works demonstration, one train of the conversion process would also be built but at only some fraction (probably one third) of commercial scale. One obvious advantage of the semi-works demonstration would be cost savings;
another might be that the semi-works demonstration could be constructed more quickly because the components would be smaller and easier to obtain. The disadvantages would be that some risk of encountering new problems in building the first commercial plant would still remain after the demonstration, and cost uncertainties with regard to building a commercial plant would be higher. Also, the reactor in a semi-works plant could not be large enough for a man to get inside and clean it, which could create maintenance problems. Furthermore, the semi-works plant would probably be useful only for the period of the demonstration because it would not be commercially viable.

Form of Support

Another issue is how demonstrations should be financed. All of the alternatives being considered include cost-sharing but in different forms. Some government contribution is required because of the uncertainties involved in a demonstration. The possibilities include:

- Sharing of total demonstration costs by industry and the federal government.
- Fixed construction subsidies with all cost overruns paid by industry.
- Loan guarantees.
- Price supports.

Some combination of these alternatives could also be used.

The amount of federal support that will be required in relation to total costs to attract bids from industry is unknown. Depending on industry perceptions of the uncertainties involved, a larger or smaller amount of federal support may be required. Current policy is to provide 50 percent of total costs, but few bids have been received since the availability of funds for demonstrations was announced a year ago. The amount of federal support that will be required to attract bids will be an indicator of the general level of uncertainty that industry attributes to synthetic fuels technology at its current stage of development; but,
as outlined in previous sections, there are so many sources of uncertainty that it will not be clear what the indicator is revealing unless accurate information can be obtained on why firms decide not to bid.

The choice of what form of support to provide for a demonstration is complicated by the different incentives to industry that each one entails. A cost-sharing policy would reduce the incentive to minimize plant costs; a construction subsidy or loan guarantee would skew the incentive for trading off capital and operating costs; and a price support mechanism could bias which synthetic fuels technologies are demonstrated, depending on prices set for different fuels.\(^1\) Price supports would also have to be substantially higher than market prices to internalize uncertainties, which might be difficult to explain to the public.

Because of the barriers to the emergence of a synthetic fuels technology delivery system discussed in Section II, the federal government may have to continue subsidizing the synthetic fuels industry beyond demonstrations, if synthetic fuels are required to meet energy needs over the next 10 to 20 years. The alternative mechanisms of support will be the same as for demonstrations; therefore, demonstrations will provide some opportunity to learn about the incentive effects of using these alternative mechanisms in later support programs.

\(^1\)For example, price supports limited to synthetic gas would undercut the demonstration of liquefaction processes.
IV. APPLICATION OF THE CONCEPTUAL FRAMEWORK

The overall purpose of Rand's study of technology demonstrations is to assess the role of demonstrations in diffusing new technology into industry. The dimensions of the conceptual framework for making this assessment are the extent to which demonstrations are useful in reducing technological, cost, and demand uncertainties; overcoming institutional barriers; and dealing with externalities. In this section, this framework will be applied to the synthetic fuels demonstrations that will be supported by the Coal Conversion Division.

TECHNOLOGICAL UNCERTAINTY

Because of the staged approach to process development used by the Coal Conversion Division, where a sequence of increasingly larger plants are developed and tested starting from bench-scale models, the basic technology of a process to be demonstrated will probably be well understood before the demonstration is conducted. Enough is known from the pilot and prior stages to be quite certain of the plant configuration and component designs needed to produce planned amounts of various synthetic fuels. However, demonstrations will be used to make certain technical refinements in plant designs. One of the most important areas will be to find technical solutions to any problems that arise from scaling process up to full scale in the demonstration from the slightly smaller scale of the pilot plant. The demonstration plant will also be where major effort will be directed to solving corrosion and wear problems. Enough data will also be collected on process dynamics to design automation systems for commercial plants.

An important result of the demonstration will be the knowledge the demonstration team acquires of the peculiarities, operating characteristics, and technical problems of their process. Although the demonstration team may publish some of this information, they will probably know much more than they will ever decide to formally disseminate. Thus, an important side effect of a demonstration will be to increase the technical capacity of the organization that designed and conducted the demonstration. This technical capacity will be
important in designing commercial versions of the demonstrated plant.

Indications are that it will not be possible to take the engineering drawings from the demonstration plant and use them to build commercial plants. Each commercial plant will have to be tailored to produce different rates of synthetic fuels, to operate on different kinds of coal, to use water from different sources, and so forth. Furthermore, the demonstration will probably reveal numerous small ways of improving plant performance that can be applied in subsequent commercial plants.

The implications for policy of this effect of demonstrations of increasing the technical design capacity of the performing organizations is that ways need to be found to assure that the best of these organizations will have sufficient sources of revenue to continue after the demonstration. As discussed in Section II, these organizations will be an important part of the synthetic fuels technology delivery system.

COST UNCERTAINTY

Demonstrations will also contribute some information on the capital and operating costs of synthetic fuels processes. Before the demonstration, engineering projections of the costs of building and operating commercial-sized synthetic fuels plan can be made, but the demonstration will provide actual data.

The amount of reduction in cost uncertainty that synthetic fuels demonstrations will be able to contribute is limited by several factors. First, because the demonstration plant will be overdesigned, its actual cost will be higher than if the plant had been built strictly for commercial purposes. Cost estimates for a commercial plant will be obtained through engineering studies of the demonstration plant; however, because of this intentional overdesign, there will be considerable room for interpretation of which costs are attributable to the demonstration. Second, the
future costs of constructing and operating a synthetic fuels plant depend on many factors exogenous to the technology, as discussed in Chapter II. These include interest rates, coal prices, equipment prices, and so forth. Depending on future increases and decreases in these cost factors, the actual costs of constructing and operating commercial synthetic fuels plants may be much higher or lower than estimates based on data from demonstrations. Ranges of possible variations in these exogenous cost factors can be made and incorporated in cost estimates but would increase the uncertainty in cost estimates based on demonstration.

Third, the cost of a synthetic fuels plant will vary greatly depending on its location, products, and owner. The significance of the ownership factor is indicated by comparing Figs. 6 and 7. The data in these figures indicate that the cost of producing synthetic fuels can vary by over 50 percent depending on the methods of financing available to an owner. For example, utilities with access to tax exempt bonds will be able to produce gas much more cheaply than private firms that have to rely on equity financing and return profits to investors. These situational factors can also be included in cost estimates but would introduce more uncertainty and would require estimates of who the owners of synthetic fuels plants are likely to be and where they will be located. To gain better understanding of these matters, the Coal Conversion Division is currently supporting a systems study that involves predicting markets for synthetic fuels and finding plant locations that minimize overall transportation costs.

Another problem in estimating costs will be difficulties in obtaining accurate information on the demonstration plant. The best source of information will be the teams of demonstration performers, but they are in competition with each other; and whether because of optimism or bias they will probably tend to underestimate the cost implications of remaining technical problems and needs for equipment. There may also be strong disagreements regarding what mathematical models should be used for cost estimating. Currently, the Coal Conversion Division has independent contractors who are monitoring the activities
of process development teams and estimating costs. No research was done for this study on the problems that these contractors are having, but an earlier attempt by the OCR to impose a common cost framework on the process development efforts met strong resistance, and it can be expected that problems will arise in the future. Currently, the Coal Conversion Division does not have a common framework for comparing the costs of alternative synthetic fuels processes.

The cost experience in the nuclear power industry supports these conclusions about the amount of reduction in cost uncertainty that can be contributed by synthetic fuels demonstrations:

- Today, 20 years after the first nuclear power reactor demonstrations, "the firm information base available to understand the current economic status of nuclear power is quite meager."

- The actual costs of constructing commercial nuclear reactors were, on the average, over three times budgeted costs in 1965 and declined only to two-and-one-half times budgeted costs in 1969.

- Although the costs of equipment from suppliers (e.g., General Electric and Westinghouse) have decreased over the years, the average actual cost of power reactors has increased substantially over the years and in the last five years has increased over 100 percent.

- The range of variation in capital costs per kilowatt of capacity varies by a factor of approximately two among power reactors completed in any given year.

**DEMAND UNCERTAINTY**

Since synthetic fuels are largely direct substitutes for natural fuels, a synthetic fuels demonstration will be of little value in generating information about demand. Furthermore, a demonstration will not provide any

---

1 Bupp.
information on the residual sources of demand uncertainty such as environmental regulations and, consequently, will not be useful in reducing the small amount of uncertainty that exists.

INSTITUTIONAL FACTORS

Throughout this case study, many different kinds of institutional barriers to the emergence of a synthetic fuels demonstration have been identified. These included:

- Regulation of gas prices by the Federal Power Commission and of fuels prices by the Federal Energy Administration, which would limit the revenues that synthetic fuels producers would earn.
- Difficulties in obtaining loans from investment bankers because of uncertainties regarding the costs of synthetic fuels technology and potential revenues.
- Possible labor union conflict.
- Lack of capacity in equipment supplier industries.
- Potential problems in maintaining partnerships between coal mine and plant owners.
- Lack of R&D capability.
Demonstrations can be useful in reducing some of these institutional barriers but cannot be expected to eliminate them. The cost information produced by demonstrations should increase the willingness of banks to loan money for synthetic fuels plants, although the increase may be small since the amount of reduction in cost uncertainty will be small. Likewise, the union agreements reached for manning synthetic fuels plants will establish precedents but not preclude later disputes. Precedents will also be set by the agreements reached between mine and plant owners, but they can not really be tested over the life of a demonstration, which will be fairly short compared with the total life of synthetic fuels plants. As discussed above, demonstrations will have some effect in building R&D organizations, but they may not alone be sufficient to maintain these organizations in the long run. With regard to affecting the FPC and FEA regulatory behavior, demonstrations will probably make little difference.

EXTERNALITIES

The most significant externalities of synthetic fuels technology will be:

- Social and economic effects on the communities and regions where plants are located.
- Environmental effects of strip mining.
- Environmental effects from the disposal of large quantities of ash and other plant waste products.

Although demonstration plants will be smaller than commercial plants, they will be large enough to conduct studies of the social and economic effects on the communities and regions in which they are
located that would be valuable information. This information may be needed in establishing future federal policy regarding where commercial plants should be located and appropriate compensation for the communities affected. To be useful for policy, any studies conducted would have to be carefully designed to sort out the effects attributable to the synthetic fuels plant from other demographic, social, and economic trends.

Synthetic fuels demonstrations will be particularly important for obtaining information on satisfactory procedures for disposing of ash and other plant wastes, since accurate predictions of the amounts of these pollutants cannot be made from pilot plant operations, where the amounts produced are much smaller than in full-scale operations. However, because pollution control measures for each synthetic fuels plant will have to be designed for the local ecology, the information produced by the demonstration plant will not totally resolve waste disposal issues.

Demonstrations are not likely to produce any information regarding the effects of strip mining on the environment and control measures that are not already known or could be studied in other strip mines.
V. CONCLUSIONS

The main purpose of this case study has been to assess the role of the demonstrations supported by the Coal Conversion Division in diffusing synthetic fuels technology into widespread commercial usage. The major barriers to diffusion have been identified as: remaining technological problems, which translate into cost uncertainty; cost uncertainty due to factors exogenous to the technology, such as interest rates and equipment prices; uncertainties about externalities, which also translate into cost uncertainties; and institutional problems. The diffusion process is also likely to involve intense political pressures that may be overriding in certain circumstances. The political pressures will exist because the stakes in synthetic fuels are so high. Synthetic fuels technology has implications for the distribution of ownership of the energy economy among energy producing firms, shares of economic growth among different geographic regions of the country, and the market power of the OPEC cartel.

VALUE OF COST INFORMATION

Reduction of cost uncertainty is central to the rate at which synthetic fuels technology will be commercially utilized. Bankers want to know how close the advertised costs of synthetic fuels plants will be to actual costs; potential purchasers want to know if costs will be low enough to make a profit at projected market prices, and the federal government needs to know costs in order to determine energy policies.

The amount of reduction in cost uncertainty relative to the amount that currently exists that demonstrations are likely to produce is small. This is largely because considerable uncertainty about the long-run costs of synthetic fuels processes will remain after the demonstration is completed. A demonstration cannot reveal the future values of many variables that are highly related to the long-run costs of a synthetic fuels process: reaction of society to large-scale disruption of the land and communities, inflation in the prices of capital equipment, future interest rates, the pattern of ownership of synthetic fuels
plants, the location of synthetic fuels plants, world oil prices and the effects on the price of coal, and future improvements in the process technology. These factors have to be included in any assessment of the long-run costs of synthetic fuels processes. The actual amount of information contributed by a demonstration will be the difference between the uncertainty in long-run cost estimates before and after the demonstration.

The amount of uncertainty before any demonstration is subject to all the same exogenous factors listed above, but will not be infinite. The fact that some synthetic fuels technologies are currently being used commercially and that the new synthetic fuels processes do not promise much improvement over these existing processes provides some baseline data. Also, considerable data will be available from pilot plant operations. Such prior information further reduces the amount of information on long-run costs that a demonstration can be expected to produce.

However, the amount of reduction in short-run cost uncertainty may be larger, especially to individual process development teams and potential purchasers of synthetic fuels plants. Demonstrations of individual synthetic fuels processes will provide information that will enable process development teams to make more accurate estimates of the costs of building a subsequent plant for a specific customer who wants to locate it in a certain place. This suggests that the cost information produced by demonstrations may be far more valuable to individual process development teams and to potential purchasers than it is to the government for purposes of establishing long-run energy policies.

Furthermore, the intense political environment deriving from the enormous financial interests at stake in the development of synthetic fuels technology and the tremendous complexity of the enterprise suggest that the federal government will have great difficulty obtaining unbiased cost information. Better information is likely to be available to investment bankers and potential purchasers of synthetic fuels plants, since their perceptions of the reliability of different process development organizations will in the long-run determine which ones survive.
ROLE OF DEMONSTRATIONS IN CREATING A TECHNOLOGY DELIVERY SYSTEM

The problems of creating a synthetic fuels technology delivery system are central to the diffusion rate of the new synthetic fuels processes into commercial use. The most critical problems are need for larger amounts of capital, the lack of capacity in equipment supplier firms, possible conflict with labor unions, the threat of regulatory restrictions on the prices that can be charged for synthetic fuels, and the lack of R&D capacity.

Similar to uncertainty reduction, the potential contribution of demonstrations to solving these institutional problems is apparently limited. Remaining uncertainty will leave potential investors unsure about committing large amounts of funds to synthetic fuels technology. Equipment suppliers are unlikely to be convinced by demonstrations alone that there will be a large enough market in the synthetic fuels to warrant substantial investments in R&D. Labor union contracts for demonstration plant operations will set precedents for future contracts but will not eliminate the possibility of disputes. Regulatory agencies are likely to be influenced more by political and economic factors than the results of demonstrations. The only area where demonstrations may be useful is in increasing the technical capacity of the R&D organizations that are involved in them.

The implication of this conclusion for the Coal Conversion Division is that rapid diffusion of synthetic fuels technology into commercial usage will require directed efforts in addition to demonstrations to solve these institutional problems. This could involve intervening in the regulatory process, working carefully with labor unions and perhaps involving them in developmental programs, taking steps to boost equipment supplier capacity, familiarizing banks with synthetic fuels technology, and finding ways of protecting synthetic fuels producers from fluctuations in market prices that do not distort long-range cost incentives. In short, if rapid diffusion of synthetic fuels technology is desired, the Coal Conversion
Division will have to direct a great deal of its effort to institutional development and will not be able to afford to concentrate only on technological development.

The rate at which synthetic fuels technology should be diffused into commercial usage is a question of national policy. If the nation continues to want energy independence by the 1980s, then synthetic fuels are one of the few feasible alternative new sources of energy. If it is decided that energy independence is not a priority national goal, then rapid diffusion of synthetic fuels technology through institutional intervention, as well as accelerated technological development, would not be needed.
OPERATION BREAKTHROUGH
(INDUSTRIALIZED HOUSING TECHNIQUES)

by

Cheryl A. Cook
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I. INTRODUCTION

HOUSING: A PROBLEM WHOSE TIME HAD COME

The civil disorders which occurred during the mid-1960's precipitated an increase in federal government concern with the problems confronting America's cities in general and urban housing markets in particular. The National Advisory Commission on Civil Disorders pointed to the connection between the unacceptable living conditions of many urban residents and the urban/racial unrest which had occurred and recommended substantial expansion of the production of directly-subsidized housing for low and moderate income families. The increased priority given to national housing policy during the Johnson Administration can be seen in two related actions: (1) the establishment of a Department of Housing and Urban Development in 1965, with the existing HHFA\(^1\) as its nucleus and a cabinet-level Secretary and (2) the appointment of two commissions—the National Commission on Urban Problems (1966), headed by former Senator Paul H. Douglas, and the President's Committee on Urban Housing (1967), headed by Edgar F. Kaiser, Chairman of the Board and President of Kaiser Industries.

In its report,\(^2\) the Douglas Commission reviewed aspects of housing production—zoning, housing and building codes, taxation, and development standards—which were assumed to prohibit the effectiveness of the residential construction industry to provide all families with adequate housing at reasonable cost. In addition, it proposed that the effectiveness of federal housing policy be measured against the achievement of national housing needs, which were to be distinguished from the demand actually articulated

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\(^1\) Housing and Home Finance Agency

through the existing market structure. The Commission concluded that meeting this need would require building 2.0 to 2.25 million housing units, including approximately 500,000 for low and moderate income families, per year over the next decade. The final report of the Kaiser Commission\(^2\) also estimated the nation's housing needs for the following decade, based on an analysis of family formation and the replacement or rehabilitation of substandard units. It recommended that 26 million additional units be built by 1978 with at least 6 million of these for low income families.

**THE CONGRESSIONAL RESPONSE: THE URBAN DEVELOPMENT ACT OF 1968**

These production goals were incorporated into the Urban Development Act of 1968, a major piece of housing legislation enacted while both the Douglas Commission and the Kaiser Committee were at work. Meeting the goal would require the production of 2.6 million housing units per year. According to the data presented in Table 1, this would constitute an annual rate of output significantly greater than previous peak levels of housing production. Furthermore, the residential construction industry in the mid-1960's appeared to be operating at or near full capacity, and attempts to expand production would probably be limited by a predicted shortage of skilled labor.

One method of alleviating this shortage would be to move much of the craft-based, on-site construction into a factory setting in which capital and less-skilled labor could be utilized more intensively. This idea was brought to the attention of Congress by Senator Douglas. Douglas appeared before the Senate Subcommittee on Housing and Urban Affairs during its hearings on the 1968 housing legislation and reported the results of the

Table 1
ANNUAL HOUSING STARTS BY TYPE, 1950 - 1972

<table>
<thead>
<tr>
<th>Year</th>
<th>Conventionally-Constructed Housing Starts&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Mobile Homes</th>
<th>Total Housing Starts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>1,951,648</td>
<td>63,100</td>
<td>2,014,748</td>
</tr>
<tr>
<td>1951</td>
<td>1,491,207</td>
<td>67,300</td>
<td>1,558,507</td>
</tr>
<tr>
<td>1952</td>
<td>1,504,520</td>
<td>83,000</td>
<td>1,587,520</td>
</tr>
<tr>
<td>1953</td>
<td>1,438,372</td>
<td>76,900</td>
<td>1,515,272</td>
</tr>
<tr>
<td>1954</td>
<td>1,550,445</td>
<td>76,000</td>
<td>1,626,445</td>
</tr>
<tr>
<td>1955</td>
<td>1,645,715</td>
<td>111,900</td>
<td>1,757,615</td>
</tr>
<tr>
<td>1956</td>
<td>1,345,739</td>
<td>104,800</td>
<td>1,450,539</td>
</tr>
<tr>
<td>1957</td>
<td>1,221,647</td>
<td>107,600</td>
<td>1,329,247</td>
</tr>
<tr>
<td>1958</td>
<td>1,375,588</td>
<td>100,400</td>
<td>1,475,988</td>
</tr>
<tr>
<td>1959</td>
<td>1,528,836</td>
<td>120,500</td>
<td>1,649,336</td>
</tr>
<tr>
<td>1960</td>
<td>1,272,137</td>
<td>103,700</td>
<td>1,375,837</td>
</tr>
<tr>
<td>1961</td>
<td>1,365,000</td>
<td>90,200</td>
<td>1,455,200</td>
</tr>
<tr>
<td>1962</td>
<td>1,492,400</td>
<td>118,000</td>
<td>1,610,400</td>
</tr>
<tr>
<td>1963</td>
<td>1,642,000</td>
<td>150,840</td>
<td>1,792,840</td>
</tr>
<tr>
<td>1964</td>
<td>1,561,000</td>
<td>191,320</td>
<td>1,752,320</td>
</tr>
<tr>
<td>1965</td>
<td>1,509,600</td>
<td>216,000</td>
<td>1,725,600</td>
</tr>
<tr>
<td>1966</td>
<td>1,195,900</td>
<td>217,000</td>
<td>1,412,900</td>
</tr>
<tr>
<td>1967</td>
<td>1,321,817</td>
<td>240,000</td>
<td>1,561,817</td>
</tr>
<tr>
<td>1968</td>
<td>1,545,500</td>
<td>318,000</td>
<td>1,863,500</td>
</tr>
<tr>
<td>1969</td>
<td>1,499,920</td>
<td>413,000</td>
<td>1,912,920</td>
</tr>
<tr>
<td>1970</td>
<td>1,466,759</td>
<td>401,000</td>
<td>1,867,759</td>
</tr>
<tr>
<td>1971</td>
<td>2,084,500</td>
<td>496,570</td>
<td>2,581,070</td>
</tr>
<tr>
<td>1972</td>
<td>2,388,500</td>
<td>575,900</td>
<td>2,954,400</td>
</tr>
</tbody>
</table>


<sup>a</sup>Conventionally constructed housing starts can be financed with either VA--and FHA--insured mortgages or convention mortgages.
Commission's work on industrialized housing. Interviews with private builders who had experimented with mass-produced housing indicated that production runs of approximately 1,000 units per year over a five year period were required in order to make a profit. As a result of this testimony, Senator Proxmire introduced an amendment to the 1968 bill (Section 108) which authorized a program to determine how mass produced methods would affect housing costs.

The purpose of the program authorized by Section 108 was:

...to encourage the use of new housing technologies in providing decent, safe, and sanitary housing for lower income families; to encourage large-scale experimentation in the use of such technologies; to provide a basis for comparison of such technologies with existing housing technologies in providing such housing; and to evaluate the effect of local housing codes and zoning regulations on the large-scale use of new housing technologies in the provision of such housing....

In order to implement this program, the Secretary of HUD was specifically authorized to:

1. Approve not more than five plans for the development of low-income housing using new and advanced technologies, which were to be submitted by public and private organizations.

2. Construct at least 1,000 housing units per year over a five year period for each of the technologies selected.

3. Conduct an evaluation of each technology, on the basis of data gathered during the construction period, in order to determine (a) the detailed cost breakdown per dwelling unit, (b) the environmental quality achieved in each such unit, and (c) the effect which local housing codes and zoning regulations have, or would have if applicable, on the cost per dwelling unit.

4. Report the findings of the evaluation to Congress together with recommendations for additional legislation required in order to expand the supply of low-income housing using those technologies which had been successfully demonstrated.

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Section 108 did not specifically authorize funds to undertake the research and development costs associated with the program outlined in the legislation. It did, however, permit the Secretary to provide mortgage insurance for the units constructed during the program under Section 233 (Experimental Housing) of the 1961 National Housing Act.

The demonstration program outlined in Section 108 was intended to determine whether the construction costs of housing could be lowered in absolute terms through the use of industrialized production methods. The thrust of Section 108 was volume production, not prototype construction to test new technologies; and the construction would be undertaken within a program of sufficient size to rigorously test the hypothesis that significant economies of scale did exist in residential construction and could be achieved within the context of an aggregated market. The operating hypothesis seemed to be that only after cost savings had been definitively demonstrated would there be sufficient interest and incentive on the part of government bureaucrats and industry participants to undertake the institutional changes necessary for their achievement in the absence of a direct government program.

**HUD's Implementation: Operation Breakthrough**

The passage of the 1968 omnibus housing bill, which was accompanied by substantial appropriations for its implementation, marked a reshuffling of domestic priorities which placed housing high on the list. The work of the Douglas Commission and the Kaiser Committee had made "the housing problem" a visible, political issue; and there was a high degree of concern in Congress for rapid, responsive federal action. However, before the policy program outlined in the 1968 bill and its Section 108 could be carried out, a new Republican administration came into office. George Romney, formerly
President of American Motors, was appointed Secretary of HUD in the new administration. Romney was thus unable to develop his own program but was faced with the task of implementing a major piece of legislation passed by a Democratic Congress and was under pressure to accomplish this task rapidly.  

In 1969, Secretary Romney announced Operation Breakthrough as the Department's response to the Congressional mandate embodied in Section 108 of the 1968 act in a series of conferences with governors, mayors and members of the residential construction industry and building trades. The program was outlined as a partnership of labor, consumers, private enterprise, local, state, and federal government which would seek to provide housing for all income levels through the use of modern techniques of production, marketing, and management.  

The implementation of this goal would be achieved in a three-part effort, which would proceed from housing system design and selection to prototype construction and testing and, finally, to volume production for housing markets which would be aggregated at the same time that the production-related steps of the program were being carried forward.

The objectives of Operation Breakthrough were outlined more completely in the Request for Proposal issued on June 23, 1969 for the development of housing systems.  

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1 During Romney's testimony before the House Subcommittee on Housing in May 1969, four months after the new administration had taken office, he was questioned repeatedly about what action HUD had taken since January toward implementing the 1968 Act and toward cutting down on existing red tape to speed the process of implementation. (Ibid., pp. 2-46.)


...the establishment of self-sustaining mechanisms for rapid volume production of marketable housing at progressively lower costs for people of all income levels, with particular emphasis on those groups and individuals which have had difficulty in obtaining satisfactory housing in the past.

The RFP also listed eight secondary objectives designed to assist in achieving the primary objective:

1. Stimulate the modernization and broadening of the housing industry through increased emphasis on better design and greater utilization of improved techniques within the current housing industry and through increased participation by other organizations that possess the necessary talents, interest and capability for such a commitment.

2. Increase participation and leadership by state and local governments in providing ongoing planning and market and site aggregation for housing, its environment and the community.

3. Waive or remove constraints to the introduction and use of tested and proven innovations in design, construction, land acquisition and use, financing, labor utilization, materials, components and systems, sponsorship, consumer participation, management and maintenance.

4. Introduce new organization concepts and management techniques for market and site aggregation and for design, production and marketing of living units.

5. Coordinate the application of all available government resources appropriate to a given site or sites for housing, environment, community services and facilities.

6. Encourage identification and development of performance standards for evaluation of innovations, working with authorities in this area.

7. Develop an ongoing testing and evaluation mechanism and technique for judging the effectiveness of innovations.

8. Develop techniques for increased effective participation by consumers and community groups in planning and developing the total housing environment.

As described by these objectives, Operation Breakthrough was a much more comprehensive program than that contained in Section 108 of the 1968 housing act. Implementing Section 108 would have proven that economies of
scale did exist for volume-produced housing but would have still left unanswered the question of how the institutional environment should be changed in order to achieve these economies outside the context of a government-supported demonstration program. According to Secretary Romney, the Breakthrough program was designed to meet both objectives.

...Operation Breakthrough...would build on the authority... provided in Section 108 of the 1968 act, but it would be a broader effort, supported by a measured commitment of the Department's resources under all its housing and housing-related programs...what we are trying to do is to focus not only technical ingenuity, but the whole complex of modern industrial management on each stage of the problem: the identification and effective use of available land; the design of the product and its environmental situation; its production; and its financing and distribution to the ultimate consumer.¹

The importance of this more global approach and the difficulties likely to accompany its implementation can be ascertained from a description of the residential construction industry in the U.S. This is presented in the next section.

¹Testimony by George Romney, National Housing Goals, p. 4.
II. THE HOUSING INDUSTRY

THE COSTS OF OUTPUT

In discussing the output of the residential construction industry, it is necessary to distinguish between (1) the production of the physical structure, the construction activities per se; and (2) the production of housing services, including land acquisition and development, marketing, financial arrangements associated with construction and purchase, and maintenance and management. The operational significance of this distinction relates to the cost of housing services and the potential for effecting significant savings in these costs by means of technological change.

Technological change in the housing industry can involve just the techniques of construction -- the development of new materials and new ways of using materials -- or it can involve the broader definition of housing output -- the development of a housing service delivery system which includes not only construction technologies but also development and marketing techniques. These two types of technological change are not independent insofar as the ability of new construction technologies to significantly reduce the costs of housing services to the final consumer may depend on their being embedded in a broader systems approach.

This interdependence is illustrated in Tables 2 and 3. Table 2 disaggregates the development and construction costs for two types of housing -- a single family detached house (three bedroom) and an apartment (3 bedroom) in a multifamily building. Table 3 accounts for the components of the monthly occupancy costs associated with these two housing units.
Table 2
DEVELOPMENT AND CONSTRUCTION COSTS FOR SINGLE-FAMILY AND MULTI-FAMILY HOUSING, PERCENTAGE DISTRIBUTION

<table>
<thead>
<tr>
<th></th>
<th>Single family Detached house</th>
<th>Apartment in Multifamily Medium-Rise Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development Costs</td>
<td>31</td>
<td>25</td>
</tr>
<tr>
<td>Land</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Development</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>6</td>
<td>12(^a)</td>
</tr>
<tr>
<td>Construction Costs</td>
<td>69</td>
<td>75</td>
</tr>
<tr>
<td>Materials</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td>On-site wages</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>Overhead/Profit</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100(^%)</strong></td>
<td><strong>100(^%)</strong></td>
</tr>
</tbody>
</table>

\(^a\)Includes the cost of hiring an architect.


Table 3
MONTHLY OCCUPANCY COSTS FOR SINGLE-FAMILY AND MULTI-FAMILY HOUSING, PERCENTAGE DISTRIBUTION

<table>
<thead>
<tr>
<th></th>
<th>Single family Detached House</th>
<th>Apartment in Multifamily Medium-Rise Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debt retirement</td>
<td>53(^a)</td>
<td>42(^b)</td>
</tr>
<tr>
<td>Taxes</td>
<td>26</td>
<td>14</td>
</tr>
<tr>
<td>Utilities</td>
<td>16</td>
<td>9</td>
</tr>
<tr>
<td>Maintenance and repair</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Administrative and similar costs</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Vacancies and bad debts</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Profit and reserves</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100(^%)</strong></td>
<td><strong>100(^%)</strong></td>
</tr>
</tbody>
</table>

\(^a\)Based on a 94.5% 30-year mortgage at 6% interest.

\(^b\)Based on an 85% 35-year loan at 6% interest.

According to the tables, a 50 percent reduction in the direct construction costs (materials and labor) of these housing units, achieved by the introduction of new construction technology, will reduce the total costs of the units by only 25 percent. A similar (25 percent) reduction would be achieved in the monthly occupancy costs of the units, by means of decreases in the mortgage value and possibly operating costs. This reduction could easily be eliminated, however, by an interest rate increase of one percent during a period of tight mortgage credit. On the other hand, it would be significantly enhanced by concomitant changes in the methods for developing land and marketing and maintaining the final structure.

It is possible to outline the likely nature of changes in construction technology (narrowly defined) by considering the relationships among the various inputs to housing construction. Residential construction in the U.S. is primarily a craft-based activity intensive in the use of skilled labor. Table 2 indicated that the costs of onsite labor account for approximately 20 percent of the total construction and development costs of a single- or multi-family housing unit; materials, roughly 38 percent; and land (excluding development), about 10 percent. The Kaiser Committee predicted that, of these three resource inputs, shortages would be most likely to occur in the case of skilled labor and land, given a demand of 2.6 million housing units per year. Such shortages would result in increases in the relative prices of these factor inputs. And these price increases could be expected

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1 Local property taxes would probably remain unchanged in order to support local services.

2 *A Decent Home*, pp. 24-26, 31-34.
to encourage factor substitutions—the substitution of less skilled labor and capital for skilled labor and, in the case of land, the development of areas where land is less expensive and/or a shift toward more intensive land use by means of substituting multi-family for single-family dwellings.

Such changes in the nature and use of housing inputs imply concomitant changes in the organization of the industry. On the supply side, the labor substitutions imply moving a portion of the craft-based, onsite activity to an assembly line, factory set-up. However, such a switch involves increases in capital and overhead costs. In order for the factor substitution to be profitable, it must be associated with economies of scale, due to the "learning curve" nature of factory-based construction and improved inventory control for materials and output, for example. Exploiting these economies of scale to reach the minimum point on the long run average cost curve requires a suitably large and stable volume of production, which depends, in turn, on a large and stable demand.

Thus a reorganization in the methods by which housing is produced requires a simultaneous change in the nature of the demand for housing. Such changes could involve (1) broadening the geographic markets for housing by eliminating local variations in building codes, for example; (2) deepening the housing market in a particular area by subsidizing the housing purchases of low and moderate income families; and (3) stabilizing the fluctuations in housing demand by easing its sensitivity to conditions in capital markets.

**INDUSTRY STRUCTURE: BUILDERS**

A preliminary estimate of the probability that shortages in the supply of land and labor will induce the type of technological and associated
organizational change outlined above without exogenous stimuli, such as
government policies, can be obtained by investigating the current structure
of the residential construction industry. The labor-intensive production
function for housing is both cause and effect of the industry structure.¹
The residential construction industry is composed primarily of a large
number of small firms operating in geographically limited markets for
relatively short periods of time. Equity capital requirements are low
relative to other manufacturing industries, and firms adjust to cyclic
nature of housing demand by leaving the industry to engage in other
activities (such as rehabilitation and remodeling) when mortgage credit
is tight and subsequently reentering when conditions improve. The fluid
nature of the industry structure is illustrated by the fact that in 1967
one-third of the approximately 110,000 homebuilding firms in operation did
not have a payroll.²

In 1969, about 17 percent of total housing production (housing starts)
was produced by large companies with an annual output of over 200 units.³
Comparable data on both the small and large firm segments of the industry
are scarce. Some notion of the operational differences between the two
segments (other than size per se) can be gained from Table 4, which is based
on the results of a 1969 survey conducted by the National Association of

¹ This discussion of industry structure is based on data for the 1960s,
rather than more recent data for the 1970s, since the earlier period was
the environment Operation Breakthrough attempted to change.

² Department of Housing and Urban Development, Housing in the Seventies,

³ Housing in the Seventies, pp. 7-9 to 7-11.
Home Builders. According to the table, homebuilders producing less than 26 units per year, which constitute the majority of the industry, are more likely to be engaged in single-family production; whereas the larger firms, especially those producing more than 100 units per year, are more likely to produce multi-family housing. These large builders tend to be comparatively stable, relatively well-capitalized corporations. This stability does not appear to be due to these firms' capability of shifting from housebuilding to other forms of construction. Instead, the large homebuilder's superior bargaining position with subcontractors, materials suppliers, etc., due to the size of his purchases, enables him to shift the burden of the fluctuations in the housing demand to the small builder.\(^1\)

This stability of production provides the large builder the opportunity to exploit any economies of scale which may exist in residential construction. According to the data in Tables 5 and 6, significant economies of

Table 5
CONSTRUCTION COSTS OF THE COMPOSITE HOUSE
CLASSIFIED BY SIZE OF BUILDER, 1962

<table>
<thead>
<tr>
<th>Output Per Firm (Number of Housing Units)</th>
<th>Cost Per House&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Cost Per Square Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>under 50</td>
<td>$15,302</td>
<td>$12.28</td>
</tr>
<tr>
<td>50-99</td>
<td>15,309</td>
<td>11.83</td>
</tr>
<tr>
<td>100-199</td>
<td>13,647</td>
<td>11.28</td>
</tr>
<tr>
<td>200 and over</td>
<td>13,487</td>
<td>11.09</td>
</tr>
</tbody>
</table>

<sup>a</sup>Cost per house does not include land.

Table 6
COSTS OF THE COMPOSITE HOUSE CLASSIFIED BY MAIN EXPENDITURES AND SIZE OF BUILDER, 1951

<table>
<thead>
<tr>
<th>Size of Builder&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Size of Builder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expenditures</td>
<td>1-24</td>
</tr>
<tr>
<td>Direct labor</td>
<td>$1,485</td>
</tr>
<tr>
<td>Direct materials</td>
<td>2,235</td>
</tr>
<tr>
<td>Subcontracts</td>
<td>3,379</td>
</tr>
<tr>
<td>Incidental</td>
<td>410</td>
</tr>
<tr>
<td>Land</td>
<td>1,250</td>
</tr>
<tr>
<td>Overhead and profit</td>
<td>741</td>
</tr>
<tr>
<td>Total cost</td>
<td>$9,500</td>
</tr>
</tbody>
</table>

<sup>a</sup>Number of housing units produced per year.
scale do exist; and the cost savings achieved by quantity purchases, inventory control, and the use of less skilled labor are not outweighed by increases in capital and overhead. Two aspects of Table 6 should be noted. First, the savings in construction costs achieved by volume production do result in lower prices to the consumer. Second, the full amount of the cost savings, however, is not passed on to the consumer; part is absorbed in the form of higher profits and overhead. In fact, the unit profits for the large builder (both the absolute amount and the percent of total costs) are nearly twice those of the small builder. This increase in profit and overhead may reflect the greater risks associated with large-scale residential construction, the exercise of monopoly power, or merely the substantial increase in overhead which accompanies volume, factory-based production.

**INDUSTRY STRUCTURE: OTHER COMPONENTS**

This configuration of supply—the predominance of small-scale builders—is determined to a significant extent by the cyclic instability of housing demand. The capital stock nature of housing production and consumption make these activities extremely sensitive to changes in the interest rate at which mortgage funds are obtained. Most buyers of new or existing housing units borrow a substantial fraction of the total cost and finance it over long periods of time, and a small rise in interest rates will significantly reduce the number of mortgage borrowers. Increases in interest rates during an upswing in the economy will thus induce lenders to shift funds into non-housing uses, such as business investment in plant and equipment, which are less sensitive to changes in interest rates. And, as a result, housing construction exhibits a countercyclic behavior over the course of the
business cycle due, in large part, to its deliberate use by policymakers as a tool for economic stabilization.

In addition to these cyclic fluctuations, the demand for housing is also characterized by its localized nature. This results from the influence of actors and institutions other than the producer (builder) and the consumer (owner/renter) on the housing market. Table 7 lists these institutional factors, classifying them according to their public or private sector status.

Table 7

THE HOUSING MARKET: ACTIVITIES AND INSTITUTIONAL FACTORS AFFECTING THE PRODUCTION AND CONSUMPTION OF HOUSING

<table>
<thead>
<tr>
<th>Function</th>
<th>Production</th>
<th>Distribution</th>
<th>Consumption and Redistribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Activity</td>
<td>Site identification</td>
<td>Site preparation</td>
<td>Construction</td>
</tr>
<tr>
<td>Specific Activities</td>
<td>Raw land speculation and turnover</td>
<td>Financing</td>
<td>Financing and sub-contracting</td>
</tr>
<tr>
<td>Primarily Public or Quasi-Public (level)</td>
<td>Transfer taxes (local)</td>
<td>Recording systems (local)</td>
<td>Zoning (local)</td>
</tr>
<tr>
<td>Primarily Private</td>
<td>Title insurance</td>
<td>Insurance standards</td>
<td>Insurance standards</td>
</tr>
<tr>
<td>Possible Institutional Factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (approx.)</td>
<td>Indefinite</td>
<td>3 months</td>
<td>6 months</td>
</tr>
</tbody>
</table>

Building codes regulate residential construction under the assumption that general, public welfare is increased by housing individuals in structurally safe units and that consumers do not have sufficient knowledge of construction techniques to judge the structural soundness of buildings. The codes are based on material specifications rather than the output performance and thus inhibit cost-saving, performance-oriented changes in materials technology. In addition, building codes contribute to market fragmentation, insofar as they are promulgated and administered at the local level.\(^1\) Although the nonstandard nature of the regulations is a constraint to improvements in construction efficiency, the fact that the codes are not uniformly enforced may constitute a more significant, but largely unidentifiable, constraint to the production of houses for a broad geographic market.\(^2\)

Zoning laws are another localized, regulatory influence on the housing market. In theory, they maximize public welfare by protecting private property values; but in practice, they may increase development costs unnecessarily and thus waste resources. Insurance standards—primarily the minimum property standards applied to FHA-insured loans—are also intended to protect private property values and safeguard the investment aspects (resale value) of housing consumption. However, the administration of these regulations is oriented toward traditional, stick-built housing and does not (or did not in the late 1960s) officially recognize the different cost structure

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\(^1\) Four model codes exist: The Uniform Building Code, the National Building Code, the Southern Building Code, and the Basic Building Code. In the mid-1960s these were used in about 60 percent of the communities with over 10,000 population. These codes have many similarities but differences continue to exist among them. Furthermore, revisions in these codes are not necessarily adopted by local communities. (Burns and Mittelback, pp. 102-103)

for factory-built housing—specifically, the inclusion of a portion of the factory overhead and capital depreciation in the mortgage value of the house.

The network of financial institutions which channel investment funds into the residential construction industry is another influence encouraging the fragmentation of housing markets. Restrictions on bank and savings and loan lending activities geographically restrict the markets into which an institution's mortgage funds can go. The financing mechanism also inhibits the adoption of factory techniques since construction lending, which is obtained by the builder to finance the actual construction of the house until mortgage funds for the purchaser are obtained, is conventionally tied to onsite construction activity.¹

The conventional wisdom of the 1960's about the operation of the residential construction industry assumed that the production inefficiencies caused by regulatory and financial institutions were exacerbated by the organization of labor supply to the industry. Unions were assumed to increase construction costs by (1) raising wages through monopolizing the supply of labor, (2) enforcing restrictive work rules which reduced labor productivity within the existing technology, and (3) inhibiting the innovation and diffusion of new technologies.

Available evidence in support of these arguments is, however, not conclusive.² The validity of the monopoly hypothesis is weakened by the fact that over 70 percent of the labor used to construct single family

¹Loan draws are related to the portion of the building's value completed on the site.

²Burns and Mittelbach, pp. 121-126.
dwellings is nonunion.\textsuperscript{1} Increases in wages for construction labor probably have not greatly exceeded increases in labor productivity since evidence on the rate of technological progress in residential construction indicates that the industry has probably been more technically progressive than conventionally assumed. In fact, the high hourly wage rates in the construction trades act as a compensation for the risks and uncertainty caused by the large cyclic swings in construction volume and the seasonal nature of construction employment. Second, conventional work practices, as opposed to official work rules, do not appear to have produced significant inefficiencies. And, third, union restrictions probably have not exercised a significant drag on the diffusion of new technology.\textsuperscript{2}

The small builder supply configuration may be a relatively efficient response to the localized nature of housing demand. This may be only static efficiency, however, and the industry may not be organized to respond efficiently over time to long term changes in demand or supply. Such dynamic efficiency depends, in part, on the ability of the industry to generate appropriate and timely responses to changed market conditions by means of research and development. However, small, undercapitalized building firms do not have the financial resources necessary for R&D activities. Nor do they have much chance of recouping the full costs of any R&D by means of


\textsuperscript{2}Note, however, that the unions' potential ability to obstruct the applications of new technology may discourage inventors from developing technologies which would achieve significant savings in labor costs.
increased sales and profits because of the competitive supply side of local construction markets.

The negative effects of this small firm market structure on R&D activities are compounded by the fragmented organization of the different phases of construction—a fragmentation which impedes the adoption of technological improvements in both product and process.\(^1\) During the design stage, architects frequently do not deal directly with builders and, therefore, may not take advantage of innovations in construction practice which could be incorporated into the building’s design. Subcontractors are engaged in the construction only after the design is completed, and thus they cannot contribute their own innovative ideas. Labor is hired to construct a fixed design and thus cannot alert architects to those aspects of the design which will present difficult and probably costly installation problems. Furthermore, housing users are fragmented and cannot readily join together to generate cohesive pressure for changes in construction technology in order to remedy errors in design and construction.

Moreover, the existing industry structure does not provide the participants with many incentives to improve the construction process. Architects’ fees are determined as a percent of the total construction value of the contract. Contracting and subcontracting procedures provide few incentives for adopting innovations which could reduce the costs of operating and maintaining the structure. Building inspectors who approve innovations are subject only to the risks of such action, not to any potential rewards.

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And financial institutions are interested in safeguarding the long term value of their investment and are unwilling to approve the use of new products or processes which might not win consumer acceptance and thus might reduce the resale value of the structure.

TECHNOLOGICAL CHANGE: THE POTENTIAL FOR IMPROVEMENT

At the beginning of this discussion of the housing industry, the distinction was drawn between the production of the physical structure and the production of housing services. Both types of housing output are amenable to technological change which would base production in factories. In terms of the first, the nature of the product supplied by the building materials suppliers would change; but the basic industry configuration of many small building firms would, at least initially, remain the same. The small builder would shift from building most of the house on site himself to the purchase and use of factory produced components, such as wall panels and utility modules, which would be produced and possibly marketed by the materials suppliers. Incorporating factory-based technology into the production of housing services would involve a change in the organization of production from small to large-scale builders. These construction firms would produce the housing components or modules, assemble them on sites which they had developed, and probably market the final product. Under such an integrated approach, the builders could internalize the benefits associated with economies of scale in production and marketing.

According to the preceding analysis, the largest savings in cost to the consumer would be achieved by the second, integrated industry type of technological change. However, such a vertical and horizontal expansion of
firm activities would mark a fundamental change in the organization of the residential construction industry. And in the absence of government policy, changes of such magnitude would be unlikely to occur or would occur only very slowly. The current fragmented supply system is probably well adapted to the fluctuating, localized nature of housing demand.

In addition, an integrated approach to the delivery of housing services marks a substantial departure from the means by which technological improvements have historically been introduced into the industry. The balance of evidence indicates that technological change in residential construction has been evolutionary in nature, introduced primarily by means of new materials and, to some extent, new products developed and marketed by building materials suppliers.\(^1\) Furthermore, the technological change that has occurred has been primarily cost saving rather than performance enhancing\(^2\)—to construct a house of a given size and quality with methods in use 25 years ago would cost substantially more than with today's techniques. However, product development based on the research activities of individual building materials firms has not led to lower cost or higher quality methods for building the structure as a whole.

The conventional wisdom prevailing in the 1960s held that residential construction was technologically stagnant compared to other U.S. industries, particularly in the manufacturing sector. Evidence to support this view was drawn from industry cost data which seemed to indicate that the real costs of building construction had risen relative to the costs of other components of


\(^2\) Although the tying of industry output and techniques to specification standards makes it difficult to measure the extent of performance-based change.
GNP. However, work done for the Kaiser Commission indicates that the relative costs of housing may not have risen as rapidly as had been previously believed and that for the period 1957-1965 the costs of housing structures may actually have declined relative to the general price level.¹

Recognizing that the housing industry was technologically more progressive than usually assumed made the task of identifying viable policies to enable it to meet the national housing goals more difficult. There did not exist an enormous "slack" within the industry which could easily be taken up by government action, even if somewhat poorly-conceived and implemented.

As long as the picture of construction as technologically rigid was accepted, there was some justification for assuming that policy to recude construction costs should be aimed at eliminating 'institutional rigidities' and 'barriers to innovation'... But the evidence that construction technology has not been rigid since 1947, makes continued exclusive emphasis on eliminating 'rigidities' and 'barriers' inappropriate. However important such factors may be (and they may indeed be important), they did not prevent construction technology from responding to market pressure over 1947-1965.²

Policy actions would have to be somewhat more sophisticated and comprehensive. And the successful implementation of programs designed to introduce the systems approach to housing production would require simultaneous action on the demand side of the market. This conclusion is supported by the post-war history of industrialized housing in Europe and the U.S.

INDUSTRIALIZED HOUSING: THE POST WAR EXPERIENCE

There had been extensive experience in the use of factory-produced housing in Europe after World War II, particularly for high-rise construction where the potential for the use of prefabricated components and subsystems was the

²Ibid., pp. 161-162.
greatest. It is difficult to generalize about the economics of the European systems in operation in the 1960s since most producers were willing to make substantial modifications to suit major individual clients and were willing to accept uneconomical contracts in terms of size and price in order to cover factory overhead and keep the factory in production. In general, it appeared that the building systems based on the use of heavy, precast concrete required an annual output of 500 - 1000 units over at least a five year period in order to achieve a 5 - 10 percent reduction in costs over traditional construction techniques for apartments. Using these systems in the U.S. might entail greater cost savings since real wage rates for construction labor in Europe were generally lower than those prevailing in the U.S.

The most important factors supporting the economic viability of the European industrialized housing systems were large volume, continuous production runs and the concentration of demand. These were attained in Europe because of the following three conditions: (1) most of the buildings constructed by industrialized techniques were part of large, concentrated, government-sponsored public housing projects; (2) the housing market in many European countries was characterized by excess demand during the 1950s and 1960s; and (3) most contracts for industrialized housing developments were not awarded on the basis of competitive bids. The operational significance of these factors was enhanced by the fact that the building systems' parent companies were able to manage, organize, produce, and market their systems as one complete package. The importance of active government support for factory-produced housing in post-war Europe should be re-emphasized. As

For further information, see the discussions in R. B. Guy, et al., The State of the Art of Prefabrication in the Construction Industry, Columbus, Ohio, Battelle Memorial Institute, 1967, pp. 48-66.
the Battelle report points out, "it is significant that the two [European] countries in which systems building has made the least progress are those where the public sector is relatively unimportant--Germany and Italy."\(^1\)

The post World War II success of industrialized housing in Europe can be contrasted to its history in the U.S. during this same period.\(^2\) The release of the pent-up demand for housing following World War II created an environment in which new construction technologies could flourish. Prefabrication appeared to be a promising candidate, and several factory-produced houses appeared on the market from the late 1940s to the early 1960s—the Acorn House (1949), the Lustron House (1947), the Techbuilt House (1954–1956), the Alside House (1961), and Academy Homes (1962). All failed to gain market acceptance.

In nearly all instances, problems with building codes, labor unions, FHA mortgage approval—all of which fall into the "barriers to innovation" category—were either avoided by careful planning at the outset of the project or overcome through a process of negotiation. The major stumbling block to the success of these projects was, instead, "the incompatibility of mass-production thinking with traditional building practice."\(^3\) The initial construction cost savings attributable to the use of nonconventional materials and standardized production were frequently eroded by the costs of site labor, land, and overhead. Attempts were made in some cases to redesign those nonconventional structural components of the house which were visually evident in order to conform more closely with consumer tastes; these efforts also added to costs.

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\(^1\) Guy, p. 51.


\(^3\) Kock, p. 40.
Most important was the failure to develop effective mechanisms for marketing and distributing the systems. Housing markets remained localized and unstable, and large volume guaranteed sales contracts failed to appear. As a result, neither the manufacturer nor the dealer/distributor could afford the carrying costs associated with inventory accumulation; and overhead costs per unit increased substantially. Decentralized production systems which subcontracted out for components and subsystems avoided fixed investments in plant and equipment (overhead) but suffered from timing problems associated with a lack of continuity among component producers and problems of quality control.

SUMMARY: THE ENVIRONMENT FOR BREAKTHROUGH

Both the Douglas Commission and the Kaiser Committee had concluded that meeting the nation's housing needs over the decade of the 1970s required the production of 2.6 million housing units per year. Such an annual rate of output would be significantly greater than previous peak levels of housing production and would probably be achieved only at substantial increases in cost, given that the residential construction industry appeared to be operating at full capacity during the 1960s. The major input constraint was a predicted shortage of skilled labor. The most straightforward method for alleviating this shortage would be to move much of the craft-based, on-site construction into a factory setting in which capital and less-skilled labor could be utilized more intensively. However, the effect of any saving in construction costs—lower unit costs due to a smaller wage bill and economies of scale—would have a less than proportionate effect on the final costs of housing to the consumer. The costs of housing services, as distinguished from the costs of the structure itself, were affected by the costs of land and development and the existence of a number of institutionally-based inefficiencies within the industry—
building codes, zoning ordinances, labor practices, etc.—which increased costs above the level that would obtain in their absence. The fragmentation of the housing supply structure and the fluctuating, localized nature of demand blunted the incentives within the industry to devise and implement the technical and institutional changes necessary to achieve significant reductions in housing costs.

Thus it appeared that, in the absence of government intervention, the residential construction industry as it existed in the mid 1960s would be unable to meet the production goal without steep increases in the cost of housing. The problem for policy was to design a program which would make the political goal of 26 million housing units a relatively low-cost physical reality.

The policy tools which were available could be targeted at (1) the stability and performance of the industry as a whole, (2) intra-industry organization and output, or (3) industry research and development activities. As finally implemented, Operation Breakthrough included the second and third of these alternatives. In terms of the second policy category, it attempted to increase the efficiency of the market mechanism for housing output by reducing the institutional barriers among the various segments of the industry (localized building codes, zoning laws, etc.). Such action was ultimately intended to increase the market incentives for privately-funded R&D, the results of which would permit the industry to respond in a timely and appropriate fashion to changes (secular as opposed to cyclic) in supply or demand conditions. The Breakthrough program gave heaviest emphasis to the third and more R&D specific policy category—the demonstration of the construction technologies embodied in the various housing systems displayed on the prototype sites.
To an important degree, however, action was required at all policy levels. The organization of housing supply in the U.S. has evolved in response to the way in which housing demand is articulated. As a result, attempts to reorganize the supply mechanism, in the direction of industrialized housing for example, without simultaneous changes in the nature of demand will have little chance of success. Factory produced housing requires the establishment of large-scale firms which, in turn, require a stable, high volume demand in order to be profitable. Government programs which demonstrate the production technology without changing the localized, fluctuating nature of housing demand will not lead to the diffusion of the technology. Such demand-related policies fall into the first category listed above. They would stabilize the industry by insulating the housing market from changes in macro-economic credit conditions—conditions presently manipulated by federal policymakers for the achievement of nonhousing goals.

From the point of view of federal policy, such a multi-faceted approach to increased efficiency in the housing sector is several orders of magnitude more complex than simply funding R&D projects to demonstrate the existence of economies of scale in residential construction. The complexity is due to the need to cut at the problem from both sides of the market at more or less the same time in ways which may involve several levels of government responsibility and bureaucracy. Furthermore, any federal action may be hamstrung by the fact that, in many respects, the locus of government activity in the housing industry (with the significant exception of credit policy) and, therefore, the available policy levers for both supply and demand exist at the state and local level.

The problems of program design and implementation with respect to increasing the efficiency of residential construction are complicated still
further by the industry’s long standing opposition to attempts by the
federal government to encourage research and development activities within
the industry. The Public Housing Acts of 1948 and 1949 authorized and
appropriated funds for a government-sponsored R & D program to investigate
the technology, economics, and building code aspects of the housing industry.
Over $5 million was allocated to the program between 1948 and 1954, but
the funding was discontinued in 1953 in response to industry opposition.
The Housing and Home Finance Agency did not have a research budget until
1962 when $375,000 was appropriated. The early research budgets of the
Department of Housing and Urban Development were also small, averaging
about $500,000 per year between 1965 and 1968.¹

The most concerted effort by the housing industry to block a federally-
sponsored R & D program occurred in 1962-63 when it helped to successfully
abort the Civilian Industrial Technology Program (CITP). CITP had been
proposed by J. Herbert Hollomon, Assistant Secretary for Science and
Technology in the Department of Commerce, to develop mechanisms for stimulating
technology transfer from the defense and space industries to the civilian
economy, including the building industry.² Building industry opposition
to the program, although not the only cause of its ultimate demise, was a
significant stumbling block to obtaining Congressional appropriations.

¹D. Nelkin, The Politics of Housing Innovation, Ithaca, New York,
Cornell University Press, 1971, pp. 75-76.

²The building research component of the program accounted for approxi-
mately one-third of the initial $3.8 million appropriations request for
Fiscal Year 1963. Its stated goals were to (1) encourage the establishment
of building science and technology centers in universities; (2) administer
and R&D grant program to develop new materials, building components, and
construction technologies, with emphasis on modular housing; (3) establish
a data base to aid in construction and land development; (4) and analyze
the nature of future technological developments and assess their likely
impacts (Nelkin, pp. 35-39).
Many congressmen argued that the CITP proposal did not represent the view of private industry and that none of the 110 trade and professional associations in the construction industry had been involved in the process by which the Department of Commerce originally conceived and designed the program. Many of these same criticisms would be leveled at Operation Breakthrough.
III. THE DESIGN OF OPERATION BREAKTHROUGH

PROGRAM COMPONENTS

Production

As stated earlier, the production-related part of Operation Breakthrough would be implemented in three phases: Phase I, Design and Development; Phase II, Prototype Construction; and Phase III, Volume Production. Phase I was expected to last for 2 to 4 months, during which time the housing system producers selected for participation in the program on the basis of an RFP competition would develop the housing technology submitted in their proposals to specific architectural designs for the prototype sites. The funding for such work would be provided by a cost plus fixed fee contract negotiated with HUD. Specifically, the contractors would be required to complete the following fifteen tasks: subsystem design and system integration, including testing; preliminary housing design; contract working drawings and construction control specifications; Phase II price quotations; prototype site planning (commenting on the preliminary site plans developed by the prototype site planners); prototype site codes and regulations (identifying local code items which would require waiver to permit the use of the building system on each site); extended (5-year) warranty feasibility study for the building system and housing units developed; and the preparation of detailed plans for management of prototype construction, prototype production, prototype testing and analysis, quality control, transportation, equal opportunity and community participation, marketing and production in Phase III, and financing.

According to Breakthrough's original program plan, approximately 1,000 prototypes of the designs developed during Phase I would be constructed in Phase II on several geographically-dispersed sites representing a variety of climatic and
market conditions. These prototypes would serve a number of purposes. They would provide the sites for testing various construction and maintenance aspects of the systems; they would be used as sales display models in order to develop market outlets for use in Phase III; and they would serve as sites for ultimate occupancy, thus permitting the testing and evaluation of the system's livability within the prototype site communities.

An important aspect of both Phase I and Phase II would be the testing and evaluation of the housing systems. HUD, therefore, contracted with the National Bureau of Standards to conduct a program of laboratory testing for the systems and to verify their compliance with established criteria.\(^1\) Once the systems were fully tested and proven to be safe, sound, and durable, they would be issued certificates of acceptability and would be permitted to market in Phase III. During this last phase of the program, the housing systems producers would manufacture their systems in volume for sale, not to HUD itself, but to the public and private instrumentalities which would be developed by HUD's efforts at market aggregation.

Obviously the way in which the Phase II prototype construction was completed would have a significant effect on the ability of the producers to market their systems successfully (without direct HUD aid) in Phase III. Several of the housing systems were to be displayed on each of the sites in Phase II in order to demonstrate the variety of housing types and price levels available to developers for purchase in Phase III. It was expected that each system producer would build on at least two sites and would construct a sufficient number of units (although certainly not enough to be regarded as volume production) to permit valid tests in the areas of production and

\(^1\)According to the housing system RFP, it appeared that these criteria would consist of the model building codes.
erection techniques, cost experience, and consumer reaction. The original program plans called for 5-7 housing systems and about 1,000 Phase II units; thus each producer would build 150-200 housing units in Phase II.

In addition to the selection of housing system producers (HSP's) and the prototype sites, planned Phase II construction required the selection of prototype site planners (PSP's) and prototype site developers (PSD'S). One site planner would be selected for each site. The firm would be responsible for the overall site design and would establish and coordinate the site planning criteria to be used by the systems producers during their Phase I design efforts. Prototype site developers (one per site) would serve as the general contractors for the Phase II construction. The housing system producer contracts for the Phase II construction would be signed with the site developers, not with the HUD Central Office.

Market Aggregation

It was recognized at the outset that the long run economic viability of the systems demonstrated in Phase II would depend on establishment of housing markets which were substantially larger than those which existed when Operation Breakthrough was first announced. Market aggregation occupied an important slot, therefore, in the initial program plans. The focus of the market aggregation effort would be the promotion of Operation Breakthrough with governors, state planning commissions, mayors and various other municipal level executives. These individuals and agencies would be asked to identify land within their jurisdictions which was suitable for further residential development. Once this land catalogue was completed, two additional studies would be prepared. The first would estimate future demand for property for residential construction on the part of both public and private instrumentalities (public housing
authorities, private developer/construction firms, etc.). The second would prepare a schedule of demand priorities over time which would relate the land types which had been catalogued to the demand projections. In order to induce state and local governments to undertake the land inventory, HUD could use $1.5 million in categorical grant and aid funds authorized under Section 701a of the 1968 housing act. Under this section, funds could be given to state and local planning agencies (or, through such agencies, to state housing finance agencies) to develop a staff and to undertake studies concerned primarily with land and site identification.

At the completion of Phase II, HUD planned to certify the housing systems which had been successfully1 demonstrated for commercial marketing in Phase III. Once this certification process was complete, HUD planned to request the housing manufacturers to undertake the requisite design work and capital investment for the mass production of their systems. With the compendium of demand estimates prepared by the state agencies, HUD could then act as the broker for Phase III, bringing together the supply and demand sides of a series of aggregated markets for industrialized housing.

THE LOGIC OF THE PROGRAM DESIGN

The program plan outlined above for Operation Breakthrough differs in scope and focus from the demonstration activities authorized by Section 108 of the Urban Development Act of 1968. Breakthrough originally planned to construct only 1,000 housing units under direct governmental sponsorship rather than the 25,000 units envisioned as the maximum output under the Section 108 program. And according to the objectives listed in the housing system RFP, it intended to take the entire residential construction industry—including labor

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1 Success in terms of safety, soundness, and durability.
unions, financial institutions, and regulatory agencies--rather than just the
direct construction component as its proper sphere of operation.

If implemented as planned, Operation Breakthrough would carry out the
legislative intent of Section 108--determining whether mass production tech-
niques would lower the construction costs of housing--only in Phase III. And
Phase III would not involve any direct government financial support for the
housing system producers, would not begin for at least two years after Break-
through itself started, and would depend for its own success on the successful
completion of the myriad of program elements contained in Phases I and II.

According to the Operation Breakthrough staff and HUD's Office of the
General Counsel, the legislative authority for Operation Breakthrough came from
Section 1010 of the 1966 Demonstration Cities and Metropolitan Development Act,
which provided funds for reducing cost and improving the quality of housing
through advances in technology, not from Section 108 of the 1968 housing act.
Congress could not, therefore, legitimately criticize Operation Breakthrough
for failing to implement Section 108 as authorized. Two questions remain,
however. First, why wasn't Operation Breakthrough specifically designed to
carry out the program outlined by Section 108 of the 1968 act? And, second,
what was Operation Breakthrough, under its non-Section 108 authority and design,
intended to accomplish?

One explanation for HUD's unwillingness to implement Section 108 can be
found in the difference in the actual construction effort contemplated by the
two programs. The construction planned in Section 108 was considerably larger
and, therefore, more expensive than Operation Breakthrough's Phase II. However, no
specific funds had been allocated to Section 108. Given the political climate
of the new administration, it did not appear likely that programs of such mag-
nitude would be approved by the Office Management and Budget. In
addition, by operating under the general research and development authority granted in the 1966 Act, the Breakthrough management team was relatively immune from political pressures from Congress regarding the program's goals, sites, and specific appropriations.

A more significant cause of the differences between Section 108 and the Operation Breakthrough plan was that the new administrative team at HUD did not feel that Section 108 addressed the relevant issues with respect to meeting the national housing goals. Secretary Romney appeared to accept the more narrow production-oriented solution implicit in Section 108. However, Harold Finger, brought by Romney from the National Aeronautics and Space Administration to fill the newly-created position of Assistant Secretary for Research and Technology, took a broader view of the housing problem and pushed the design of Breakthrough beyond construction per se toward the community-development approach apparent in the housing system RFP. Both men agreed that the solution to the supply constraints present in the housing industry would be found in modern management techniques.

There were, however, a number of problems inherent in such a broadly-based approach—problems evident even before the practical details of implementation interfered with the achievement of program goals. The objectives of Operation Breakthrough, as stated in the housing system RFP and reiterated in the program's publicity, were potentially in conflict. Was Breakthrough going to produce hard products (houses, housing factories) or institutional change (a performance-based building code embedded in new state-wide codes) or both? Was the focus of Breakthrough research and development or demonstration? Would most of the program effort be devoted to the development of new technologies for housing production, taking the housing systems selected for the program from R&D to commercial application; or would the program concentrate on
demonstrating the economics of factory-built housing? With an unlimited budget and an unlimited amount of time, these goals would not necessarily be mutually exclusive. The imposition of resource constraints, however, meant that choices would have to be made with respect to which goals would be emphasized, which phase of the program would receive the most time and money, and, therefore, which housing system technologies would be demonstrated.

The current (post Phase II) rationale from the Breakthrough management team for the presence of such conflicts within the program is twofold. First, they claim that a systems approach was required: "...any attempt to treat one element or only a few elements of the problem will probably not provide the means for solving the problem generally."\(^1\) Second, they argue that the hard products (houses) were a necessary vehicle to facilitate the creation of the more difficult but more important institutional changes. "It was felt that achieving institutional change and elimination of constraints in the various elements of the housing business had to be encouraged by some visible focus--by some physical example."\(^2\)

Both of these arguments do have some validity. First, according to the analysis of the residential construction industry presented in Section II, increased efficiency in the production of housing units would be obtained only by a simultaneous reorganization of demand and supply; and this amounts to a systems analysis of U.S. housing markets. Second, the active opposition and inertia which inhibits institutional change is frequently based on arguments of the "conventional wisdom" variety. The use of physical examples will provide

\(^1\) H. Finger, "Encouraging Innovation in Housing," Speech prepared for the Fourth Inter-American Congress of Housing, Mexico City, Mexico, October 28-November 2, 1973, p. 2.

\(^2\) Finger, p. 7.
up-to-date "hard" data with which the validity of such arguments can be re-examined. The description of previous attempts at introducing industrialized housing into the U.S. market, indicated that many of the institutional constraints--labor unions, building codes, etc.--could be either avoided or accommodated. Therefore, by constructing a sufficiently large number of houses of different types in different environments, HUD might be able to generate a large enough sample of data to make permanent those institutional changes which had been previously achieved only as temporary exceptions.

However, even this strategy for achieving institutional change--a systems approach which includes hardware-oriented technology as an instrument (not a goal)---implies some ordering of the goals and timing of the components of an institution-oriented demonstration project as complex as Breakthrough. Specifically, it implies that minimal amounts of time and money be allocated to putting the hard products in place and making them operational. The majority of the program resources and staff time would be spent using these products as a means to achieve the institutional ends.

SELECTION OF THE PARTICIPANTS

Housing Systems Producers

The first request for proposals during Operation Breakthrough was for the housing system producers and was issued on June 23, 1969 to approximately 5000 companies.\textsuperscript{1} Two types of proposals were sought: Type A for the design, testing, and evaluation of complete housing systems; and Type B dealing with both hardware and software concepts related to housing which required further design and development before being ready for prototype construction or commercial application. The proposal requirements were complex and

\textsuperscript{1}HUD RFP H-55-69.
preparing a proposal which was responsive both to Breakthrough's broad primary and secondary objectives, as stated in the RFP, and to the specific questions regarding the building system being proposed necessitated a substantial commitment of resources by the respondent.

Given the nature of the proposal, HUD expected only 50 to 100 responses despite the large number of RFPs which had actually been issued. However, by the closing date of September 19, 1969, it had received 601 responses. Of these, 236 were considered Type A; and an initial screening to eliminate those proposals which were clearly inadequate or nonresponsive further reduced the number to 136. An enormous evaluation task remained, however. The proposals covered a broad range of housing types, construction materials, and innovations in both construction technology and marketing and distribution. Most contained a mass of data;\(^1\) although some of the data, especially that related to costs, was vague and imprecise.\(^2\) This made strictly numerical comparisons, such as dollar costs per square foot, across proposals impossible and complicated the detailed, quantitative evaluation procedure.

The evaluation was carried out according to official HUD procurement policies. The proposals were reviewed by a 14-member Proposal Evaluation Board, which was assisted by four committees--Building Systems, Site Systems, Management Systems, and Financial Systems. Because of the proprietary and confidential nature of much of the

\(^1\) Some of the proposals were over a foot thick.

\(^2\) 423 proposals were released for publication and appear in U.S. Department of Housing and Urban Development, Housing Systems Proposals for Operation Breakthrough, U.S. Government Printing Office, Washington, D.C., December 1970. Most of these are deficient in cost-related data.
information included in the proposals (primarily unpatented innovations and cost data), the members of both the Board and the Committees were drawn solely from HUD and other federal government agencies.\textsuperscript{1} The proposals were graded according to a weighted system of 1000 maximum points arrayed as follows: Building Systems (320 points), dealing with the system's practicability, durability, produceability, and costs; Site Systems (235 points), concerned with the proposer's ability to adapt the system to varying site conditions; Management Systems (235 points), dealing with the proposer's organizational capability to undertake the contract tasks in Phases I, II, and III; and Financial Systems (210 points), concerned primarily with the proposer's financial capability to undertake those capital and operating costs which would not be reimbursable by the Breakthrough contracts. In addition to these producer-specific criteria, there were a number of program criteria which HUD interjected into the evaluation process. HUD wished to demonstrate a variety of systems in Phases II and III and, therefore, wanted the systems to span a range of building materials, housing types (single- and multi-family, low- and high-rise), costs, and innovativeness (both conventional and innovative systems). Furthermore, under the assumption that increased efficiency in residential construction would be achieved by a consolidation of the industry, HUD believed that the producers selected for Breakthrough should be mostly large-scale, professionally integrated or consortia-type contractors.\textsuperscript{2} It is not clear what tradeoffs

\textsuperscript{1}It is a matter of conjecture whether this government-only restriction limited HUD's ability to assemble at short notice the expertise required to evaluate the Breakthrough housing systems proposals; the evaluation deliberations were confidential.

 existed among these various proposal- and program-related evaluation
criteria, nor how they were resolved in the final selection process.¹

On the basis of a rank-order vote by the Evaluation Board, 37 systems
entered the final stages of the competition in December 1969. Of these
37, 22 were announced on February 26, 1970 as housing systems producers
for Operation Breakthrough. These producers are listed in Table 8 along
with a summary of the characteristics of the systems built in Phase II.
Most of the housing system producers (HSPs) were already active in the
residential construction industry as builders, contractors, or materials
suppliers, although they did not necessarily use factory-based technology.
Among the HSPs which were newest to the housing industry were Republic
Steel, Alcoa (although it had been producing service modules and other
building materials), and the four firms whose Breakthrough proposals were
spinoffs of previous work in the aerospace and defense industries—Material
Systems, TRW, Pantek Inc., and General Electric, which had developed its
factory-based housing system under contract with the Department of Defense
for the purpose of supplying military housing needs.

The producers had only three months to respond to the RFP. As a
result, the systems represented basically off-the-shelf technology. Several
were offshoots of housing systems already in production for the U.S. market—
Boise Cascade, Christiana Western, FCE-Dillon Inc., Home Building,
Scholz, and Stirling Homex. In addition, three of the winning producers
proposed to demonstrate precast concrete panel systems which had already been

¹A member of the Management Systems Evaluation Committee said
that, of the 22 producers finally selected, the committee felt that
seven would potentially experience management (including financial)
difficulties. Four of these later did have problems, not unrelated
to Operation Breakthrough itself.
<table>
<thead>
<tr>
<th>Producer</th>
<th>Dwelling Type</th>
<th>Optimum Density/Acre</th>
<th>Structure</th>
<th>Principal Innovation</th>
<th>Off-Site Construction</th>
<th>Estimated System Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alcoa Construction Systems Inc.</td>
<td>SFD, SFA, MFLR, MFMR, MFHR</td>
<td>3-75+</td>
<td>Wood/aluminum panels; wood service modules</td>
<td>Service modules are core around which any home may be custom designed and built</td>
<td>Panels and service modules</td>
<td>$10 to $20 per sq. ft.</td>
</tr>
<tr>
<td>Boise Cascade Housing Development</td>
<td>SFD, SFA, MFLR</td>
<td>4-30</td>
<td>Steel and wood-frame box-modules</td>
<td>Wide variety of modular arrangements-determined by planned interior usage</td>
<td>Finished box-modules</td>
<td>Medium</td>
</tr>
<tr>
<td>Building Systems International</td>
<td>SFA, MFLR, MFMR, MFHR</td>
<td>10-150</td>
<td>Precast concrete panels, slabs and service modules</td>
<td>Ballency (European) system combines materials and techniques</td>
<td>Panels, slabs and service modules</td>
<td>Unknown</td>
</tr>
<tr>
<td>CAMCI, Inc.</td>
<td>MFMR, MFHR</td>
<td>50-250</td>
<td>Precast reinforced concrete panels for walls and floors</td>
<td>Combination of precast concrete wall and floor panels and improved joint techniques</td>
<td>Wall and floor panels</td>
<td>Less than conventional</td>
</tr>
<tr>
<td>Christiana Western Structures</td>
<td>SFD, SFA, MFLR</td>
<td>4-25</td>
<td>Wood framing and pre-cut panels</td>
<td>Standardized factory-built framing sub-assemblies</td>
<td>Wood framing and pre-cut panels</td>
<td>Compatible to conventional</td>
</tr>
<tr>
<td>Descon/Concordia Systems Ltd.</td>
<td>MFLR, MFMR, MFHR</td>
<td>20-200</td>
<td>Precast concrete panels</td>
<td>Elements and assemblies produced in existing facilities</td>
<td>All concrete elements and service modules</td>
<td>Comparable to conventional</td>
</tr>
<tr>
<td>FCE-Dillon Inc.</td>
<td>SFA, MFLR, MFMR, MFHR</td>
<td>4-125</td>
<td>Precast concrete panels and service modules</td>
<td>Combination of precast concrete wall and floor panels, and service modules</td>
<td>Pre-cast walls and floors, and service modules</td>
<td>$16 to $23 per sq. ft.</td>
</tr>
<tr>
<td>General Electric Company</td>
<td>SFA, MFLR</td>
<td>5-30</td>
<td>Box-modules with steel studs and plywood stress-skin panels</td>
<td>Cast-plaster walls</td>
<td>Finished box-modules</td>
<td>Medium (235/236 apply)</td>
</tr>
<tr>
<td>Producer</td>
<td>Dwelling Type&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Optimum Density/ Acre</td>
<td>Structure</td>
<td>Principal Innovation</td>
<td>Off-Site Construction</td>
<td>Estimated System Cost</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>---------------------------</td>
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<td>----------------------------------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Hercules Inc.</td>
<td>SFA, MFLR</td>
<td>5-15</td>
<td>Wood-frame box-modules</td>
<td>Vertical and horizontal arrangement of modules</td>
<td>Finished box-modules</td>
<td>Costs vary</td>
</tr>
<tr>
<td>Home Building Corporation</td>
<td>SFD, SFA, MFLR</td>
<td>10-20</td>
<td>Wood-frame box-modules</td>
<td>Factory-built modules</td>
<td>Finished box-modules</td>
<td>$14 per sq. ft.</td>
</tr>
<tr>
<td>Levitt Technology Corporation</td>
<td>SFA, MFLR</td>
<td>3-27</td>
<td>Wood-frame box-modules</td>
<td>Modules produced in modern (1971) built-for-purpose factory</td>
<td>Finished box-modules</td>
<td>Comparable to conventional</td>
</tr>
<tr>
<td>Material Systems Corporation</td>
<td>SFD, SFA, MFLR</td>
<td>4-20</td>
<td>Box-modules assembled from plastic wall panels or field erected panel construction</td>
<td>Man-made (plastic) material</td>
<td>Finished box-modules or panels</td>
<td>Low to medium-low (235/236 apply)</td>
</tr>
<tr>
<td>National Homes Corporation</td>
<td>SFD, SFA, MFLR</td>
<td>3-18</td>
<td>Wood/steel-frame box-modules or panel assemblies</td>
<td>Factory-built modules or panel assemblies</td>
<td>Finished box-modules or panel assemblies</td>
<td>Costs discussed by specific project only</td>
</tr>
<tr>
<td>Pantek Corporation</td>
<td>SFD, SFA, MFLR</td>
<td>10-30</td>
<td>Load-bearing aluminum edge sandwich panel and service modules</td>
<td>Home can be built by owner with little equipment due to small panel system</td>
<td>Panels and service modules</td>
<td>Less than conventional</td>
</tr>
<tr>
<td>Pemtom Inc.</td>
<td>SFD, SFA</td>
<td>8-15</td>
<td>Wood-frame box-modules</td>
<td>Factory-built modules with 12-ft clear span capability</td>
<td>Finished box-modules</td>
<td>Comparable to higher price conventional construction</td>
</tr>
<tr>
<td>Republic Steel Corporation</td>
<td>SFD, SFA, MFLR</td>
<td>4-7</td>
<td>Steel-faced floor, wall and roof panels; steel angle frame</td>
<td>Structural panel system</td>
<td>Panels; mechanical, plumbing and electrical subsystems</td>
<td>$20,000 for 3BR, $25,000 for 4BR</td>
</tr>
<tr>
<td>The Rouse-Waters Company</td>
<td>MFLR, MFP, MFRH</td>
<td>15-100+</td>
<td>Precast concrete panel and slab</td>
<td>Wates (English) structural system</td>
<td>All concrete above first floor; R/Bath modules</td>
<td>6% less than conventional</td>
</tr>
</tbody>
</table>
Table 8--Continued

<table>
<thead>
<tr>
<th>Producer</th>
<th>Dwelling Type&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Optimum Density/Acre</th>
<th>Structure</th>
<th>Principal Innovation</th>
<th>Off-Site Construction</th>
<th>Estimated System Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scholz Homes Inc.</td>
<td>SFA, MFLR</td>
<td>8-16</td>
<td>Wood-frame box-modules</td>
<td>Factory-built modules with conventional appearance</td>
<td>Finished box-modules</td>
<td>$14 to $16 per sq. ft.</td>
</tr>
<tr>
<td>Shelley Systems Inc.</td>
<td>MFLR, MFMR, MFHR</td>
<td>10-200</td>
<td>Precast concrete box-modules</td>
<td>Vertical checkerboard arrangement of modules</td>
<td>Finished box-modules</td>
<td>10-20% less than conventional</td>
</tr>
<tr>
<td>Stirling Homex Corporation&lt;sup&gt;c&lt;/sup&gt;</td>
<td>MFHR</td>
<td>50-300</td>
<td>Box-modules and steel framing combined in field</td>
<td>Erection technique</td>
<td>Finished box-modules</td>
<td>Medium</td>
</tr>
<tr>
<td>Townland Marketing and Development Corporation</td>
<td>SFA, MFLR  (Structure is MFMR/HR)</td>
<td>10-100+</td>
<td>MFMR/HR super-frame with modular or panel dwellings</td>
<td>&quot;Created land&quot; in air</td>
<td>Precast super-frame, panels/modules. Utility distribution packages.</td>
<td>Unknown</td>
</tr>
<tr>
<td>TRW Systems Group</td>
<td>SFD, SFA, MFLR</td>
<td>13-25</td>
<td>Box-modules assembled from plastic wall panels or field erected panel construction</td>
<td>Man-made (plastic) material</td>
<td>Finished box-modules and panels, and service units</td>
<td>More than conventional</td>
</tr>
</tbody>
</table>

<sup>a</sup>These describe the systems which were actually constructed in Phase II, which were not, in many cases, identical to those originally proposed to HUD. The most substantial changes occurred in the housing systems of Christiana Western, National Homes, Pemtom, and Townland. See the discussion in the text, pp. 62-63.

<sup>b</sup>The following notation is used for the housing types: SFD, single-family detached; SFA, single-family attached; MFLR, multi-family low-rise (garden apartment); MFMR, multi-family medium rise; and MFHR, multi-family high rise.

<sup>c</sup>Stirling Homex went bankrupt and did not build in Phase II.

used extensively in Europe—Building Systems International (the Balency System), Camci (the Tracoba System), and Rouse-Wates (the Wates System).

Three high-technology housing systems were actually demonstrated in Phase II: (1) Material Systems, which used a fiber-reinforced resin and filler to fabricate the system's structural and decorative panels; (2) TRW, which used a mandrel-wrapped, fiber-shell module; and (3) Descon/Concordia, which developed a totally coordinated and complete system of concrete panels, interior partitions and exterior wall units incorporating heating and air-conditioning systems. The system originally proposed by Pemtom utilized a major innovation in the form of a polymer bonding adhesive (developed by 3M) which would replace heavy nailing. Problems in evaluating the adhesive during Phase I, however, led to its elimination from the Pemtom system.

The systems selected for Breakthrough did represent the variety of structural concepts and materials desired by HUD, although it is not clear how and at what cost, with respect to other criteria, this fell out of the evaluation process. Based on their characteristics at the time of selection, the systems can be categorized as follows:¹

| basic structural concept: | volumetric (modular) | 10 |
| | panel | 9 |
| | component subassemblies | 3 |

| principle material used: | concrete | 6 |
| | metal | 1 |
| | wood | 8 |
| | plastic | 2 |
| | composite | 5 |

Sites

The prototype sites for the Phase II construction were solicited by a letter and attached questionnaires sent to governors and mayors on August 6, 1969. Communities were requested to offer sites on which they would be willing to waive local building codes and zoning ordinances for the purposes of the Phase II construction. By the closing date of September 19, 1969, 218 sites had been proposed by communities in 36 states and the District of Columbia.\(^1\) As in the case of the housing system RFP, the size of this response was greater than expected. The evaluation task was complicated further by the fact that the quality of the sites proposed tended to be low—many were sites already designated for urban renewal which had not yet been built on—and thus less desirable for the highly publicized, marketability oriented construction program planned for Phase II.

On the basis of the work of a Site Evaluation Board, the following eleven sites were selected to represent a range of geographic, climatic, and marketing conditions:\(^2\)

1. **Houston, Texas.** The site consisted of 15 acres in Harris County, about 3 miles outside the city limits in the Clear Lake area.

2. **Indianapolis, Indiana.** The site consisted of 43 acres on the periphery of the city near the Indianapolis Speedway. Downtown Indianapolis was approximately five minutes away by car.

\(^1\) A list of the proposed sites is contained in HUD, *Housing Systems Proposals for Operation Breakthrough*, p. 585.

3. **Jersey City, New Jersey.** This site was composed of 6.4 acres in the St. John's urban renewal area in the center of Jersey City. Downtown Manhattan was 20 minutes away by rapid transit.

4. **Kalamazoo, Michigan.** This was a 34 acre site on a plateau on the outskirts of Kalamazoo, overlooking a lake in Spring Valley Park.

5. **King County, Washington.** This was a 36 acre site, located about 20 miles from Seattle near the village of Woodinville. Initially, the site was somewhat isolated; but neighborhood growth kept pace as the Phase II construction was completed.

6. **Macon, Georgia.** The site consisted of 50 wooded acres on the southwestern edge of Macon, 4.5 miles from downtown. It was previously a private sportsman's retreat and included a six-acre lake.

7. **Memphis, Tennessee.** This was a 16 acre site located in the Court Avenue urban renewal area, and adjoining the downtown business district and the University of Tennessee Medical Center.

8. **Sacramento, California.** This was a 30 acre site, about four miles southwest of downtown Sacramento. Formerly part of the California State Fairgrounds, the site was flat and featureless, in contrast to the similar-sized suburban sites in King County, Kalamazoo, and Macon.

9. **Seattle, Washington.** This was a 2 acre site in the Yesler-Atlantic Neighborhood Improvement Project in downtown Seattle and was part of the Central Area Model City. It was originally considered a subsite of the King County site.

10. **St. Louis, Missouri.** This site consisted of two parts, three city blocks apart, in the Mill Creek urban renewal area, which was about one mile from downtown St. Louis. The area between the two sites was an established urban renewal neighborhood, Laclede Town.

11. **Wilmington, Delaware.** This was a wooded, 100 acre suburban site, located about five miles from downtown Wilmington, on part of the state-owned Ferris School for Boys.

A funding cutback in the summer of 1971 (for Fiscal Year 1972) forced the deletion of two sites and 900 units. The smallest amount
of progress had been made on the Wilmington and Houston sites due to political difficulties.\(^1\) Therefore, these were dropped from the original list.

**Prototype Site Planners**

Three hundred RFPs were issued on August 26, 1969 for the solicitation of firms to undertake the design work for the prototype sites. These contractors would be responsible for the overall site design and would coordinate the planning criteria which would be used by the housing system producers in designing their specific systems applications. The planners would assist in the allocation of systems across sites and would coordinate the location of the systems within each site. As described by the RFP, the prototype site planner would undertake a comprehensive effort to design a site which interfaced both with the community and with the housing systems themselves—a design capability which exceeded the state of much residential site design work at the time the RFP was issued.\(^2\)

The preparation and subsequent evaluation of the design proposals was complicated by the fact that neither the sites nor the housing systems were

\(^1\)Legal proceedings were either planned or underway to prohibit the Phase II construction planned for the two sites. In Wilmington, low income families saw Breakthrough as a program which would use federal subsidy money to build middle and upper class housing. In Houston, the project was opposed by upper income families. The site was located in an area inhabited by NASA people who wanted to sell their homes (the NASA program was phasing out) and were concerned that property values would fall with the arrival of low income families in the Breakthrough housing.

known, the selection of all three components (sites, houses, planners) having been undertaken simultaneously. As a result, the evaluation criteria included such factors as design capability, familiarity with advanced building systems, and professional staff competence in the fields of architecture, planning, landscape architecture, and civil engineering. Eighty-two proposals were received; the firms selected and sites to which they were assigned are given in Table 9.\(^1\)

**Prototype Site Developers**

The prototype site developers were selected on the basis of proposals (68 in total) written in response to an invitation published in the *Federal Register* on April 18, 1970.\(^2\) The winning firms, listed in Table 9, were the last major Operation Breakthrough participants selected. Whenever possible HUD wanted the developers, who would act as the Phase II general contractors, to be local firms from each site community in order to facilitate the acceptance of the Phase II project by the community and encourage community participation in the project's development and ultimate occupancy.

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\(^1\) The firms selected for two sites subsequently eliminated were RTKL, Inc. for the Wilmington site and Caudill, Rowlett, and Scott for Houston.

Table 9
THE ASSIGNMENT OF THE PROTOTYPE PLANNERS AND PROTOTYPE DEVELOPERS TO THE PHASE II SITES

<table>
<thead>
<tr>
<th>Sites</th>
<th>Prototype Site Planners</th>
<th>Prototype Site Developers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indianapolis, Ind.</td>
<td>Skidmore, Owings &amp; Merrill of Washington, D.C.</td>
<td>Urban Systems Development Corporationa</td>
</tr>
<tr>
<td>Jersey City, N.J.</td>
<td>David A. Crane of Philadelphia</td>
<td>Volt Information Sciences</td>
</tr>
<tr>
<td>Kalamazoo, Mich.</td>
<td>Perkins and Will of Chicago</td>
<td>Bert L. Smokler/National Corp. for Housing Partnerships</td>
</tr>
<tr>
<td>King County, Wash.</td>
<td>Eckbo, Dean, Austin &amp; Williams/George S. Nolte of San Francisco</td>
<td>The Boeing Company</td>
</tr>
<tr>
<td>Macon, Ga.</td>
<td>Reynolds, Smith, &amp; Hills of Jacksonville, Florida</td>
<td>Fickling and Walker/National Corp. for Housing Partnerships</td>
</tr>
<tr>
<td>Memphis, Tenn.</td>
<td>Miller, Wilhry, and Brooks of Louisville, Kentucky</td>
<td>Alodex</td>
</tr>
<tr>
<td>Sacramento, Ca.</td>
<td>Wurster, Bernardi &amp; Emmons of San Francisco</td>
<td>Campbell Construction Co./National Corp. for Housing Partnerships</td>
</tr>
<tr>
<td>Seattle, Wash.</td>
<td>Building Systems Development of San Francisco</td>
<td>The Boeing Company</td>
</tr>
<tr>
<td>St. Louis, Mo.</td>
<td>Hellmuth, Obata and Kassa-baum of St. Louis</td>
<td>Millstone</td>
</tr>
</tbody>
</table>

aThis was a subsidiary of Westinghouse Corporation.
IV. THE IMPLEMENTATION OF BREAKTHROUGH: PHASE I

PROGRAM EMPHASIS

The decisions made during the early months of the program were driven by two related goals which had more relevance to HUD as a department and George Romney as its Secretary than to Operation Breakthrough as a specific program within HUD. Romney was under considerable political pressure to implement the 1968 Housing Act and thereby alleviate the nation's housing problem. As a result, he needed a large, highly visible program which was national in scope, industrywide in design, and capable in theory of delivering a solution to the entire housing problem in one fell swoop. Such a program became Operation Breakthrough—not in a manifestation which would follow the intent of Section 108 of the 1968 act, but in one which would demonstrate many housing systems by the construction of many housing units on many sites in a short period of time.

This goal was reinforced (and undermined) by a second policy decision to undertake what was termed "defensible" research. In 1968, Congress had criticized HUD's research program as one which produced paper studies (information) which accumulated dust on a bureaucrat's shelf rather than action-oriented analyses which led to change in the field. Romney elevated the Office of Research and Technology to the level of Assistant Secretary, named former NASA official Harold Finger as its first incumbent, and initiated an increase in...
in its Congressional appropriations from $500,000 to over $10 million. Thus, both Romney and Finger had a personal stake in proving that HUD could conduct responsive and responsible research, and, as a result, adopted a management strategy for Operation Breakthrough which was intended to operate the program on time and on budget and produce hard (i.e., defensible) products.

These policy level decisions to use Operation Breakthrough as a demonstration of HUD's efforts to move ahead on the 1968 housing act and its ability to do "hard" research led to the emphasis at the program level of the Phase II prototype construction. The nature of this construction effort still had to be decided, however. The original plan programmed Phase II construction at 5 to 7 producers, building a total of 1000 units. The size of the response to the housing system RFP and Romney's desire for a large Phase II effort pushed these output goals up to 22 producers and 3000 units. Despite (or perhaps because of) this larger absolute size, Phase II could have demonstrated the technology-related parameters of industrialized housing—technical feasibility, cost, marketability, implications for changes in existing building codes, etc.—by a straightforward construction program which simply put housing units on sites.

Assistant Secretary Finger, on the other hand, believed that if Operation Breakthrough was to have any hope of revolutionizing the housing industry, whatever it demonstrated had to be done within a community context rather than within the standard land development or federally-subsidized housing approach which "simply put housing

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1Only to the extent that costs related to volume production could be extrapolated from the prototype experience.
units on sites." The process by which this community development was to be accomplished was not fully conceptualized at the beginning of the program. Eventually, it was embodied in the design of prototype housing systems and sites which were suitable for all income groups, not just the low income households which had been the target of Section 108. This decision led to increases in the costs for site design and development and for the design and evaluation of the housing systems above the amounts which had been originally budgeted for these activities. Given the policy decision to live within the original funding level of $60 million for all three phases, other non-construction parts of the program were cut back and the Phase II construction was eventually mortgaged out with private financing.

The community development emphasis given Phase II can be justified as a decision which overburdened and overcomplicated a research program already swamped with multiple and conflicting goals which could not all be achieved within the available time and dollar budget. In retrospect, however, demonstrating the viability of a housing development which is racially and economically integrated may be one of Operation Breakthrough's most significant accomplishments. American urban development has historically been dominated by a neighborhood life-cycle known as the "trickle-down" process, which has been one of the many factors contributing to the decay of the inner city in metropolitan areas.\(^1\) By definition, programs which

\(^1\)Due to the costs of construction and land development (including the costs of complying with building codes and zoning laws), only households in the upper half of the income distribution in the United States could afford to live in new, unsubsidized housing in the late 1960s. Such housing was usually constructed on vacant lands surrounding built-up neighborhoods. The remaining households lived in
seek to end and reverse this urban degeneration must reduce the concentration of poverty in the inner city. An important mechanism for achieving this would be the creation of housing developments in both urban and suburban areas which contain a mix of racial groups and income levels. If the mixed communities established on the Breakthrough prototype sites survive, the feasibility of this type of housing development will have been established. According to an Urban Institute report, this is the most important Operation Breakthrough issue currently facing the prototype sites.¹

**TESTING AND EVALUATION OF THE HOUSING SYSTEMS: THE GUIDE CRITERIA²**

According to the original program plan, Phase I would be a two to four month design and development effort which would concentrate on testing and evaluation of the housing systems prior to their actual construction in Phase II. Developing a sound, reliable set of evaluation procedures for Phase II was important because the prototypes were to be constructed on sites which waived or removed existing building code and zoning restrictions. In setting aside this traditional acceptance procedure,

the existing housing inventory within the urban area, with the poorest households occupying the units in the center. As the new units occupied by the most affluent households aged, these households moved on to newer, more suburban areas; and lower income households moved in. Neighborhoods would eventually turn into slums if income groups too poor to support the maintenance costs of the housing moved in. The concomitant migration of retail and manufacturing firms (and thus employment opportunities) to the suburbs in search of lower-cost operating conditions and better markets reduced the economic resources of these neighborhoods still further.

¹D. Weidman, F. Tolson, and J. Wholey, Summary of Initial Assessment and Evaluation Study Design for Operation Breakthrough, The Urban Institute, Washington, D.C., May 1, 1974, pp. 9, 15.

HUD thus accepted the responsibility for evaluating and certifying the health and safety aspects of the housing as well as its durability, livability, and marketability. Ultimately, the evaluation procedure developed would be used to certify those systems deemed suitable for volume production in Phase III.

The housing system RFP implied that the evaluation criteria for the Breakthrough housing would be drawn from the nationally-recognized model codes, subject to modification where the code provisions appeared to be too stringent. Early in Phase I, however, it became evident that the specification orientation of the model codes did not provide an adequate basis for evaluating the innovative aspects of the housing systems under review. Technical evaluation would, therefore, have to be based on performance requirements, criteria, and tests.

Although this decision to use performance criteria was undoubtedly the most rational decision in terms of building the Breakthrough housing systems and increasing the incentives for and feasibility of future innovation in the housing industry, it became an extremely costly one in terms of Breakthrough's timetable and budget. Phase I was scheduled to run from approximately October 1969 until April 1970 but, in fact, lasted from July 1970 until August 1971. The delay in the contract negotiations and fulfillment of the Phase I contract tasks can be attributed, in part, to bureaucratic red tape, the inability of the

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1 The RFP requested the producers to indicate where their proposed system differed from or was in conflict with the provisions of the following model codes: Building Officials Conference of America (BOCA) Code, Southern Building Code, Uniform Building Code (ICBO), National Building Code, National Electric Code, National Plumbing Code, Uniform Plumbing Code, and BOCA Plumbing Code. (HUC RFP No. H-55-69, p. C-14.)

2 Some of the systems were not finally approved for Phase II construction until December 1971.
manufacturers to perform on time, and what were probably unrealistically optimistic deadlines. The Phase I contracts involved approximately 18 tasks, each reimbursable on a cost plus fixed fee basis, and not all producers had developed their systems to the same point when the contract negotiations began. Thus monitoring and coordinating the Phase I effort was a major task for the Breakthrough management.

These problems were all, however, subsidiary to (and partially caused by) difficulties associated with the use of performance oriented evaluation criteria for the housing systems. Since no comprehensive set of such criteria existed in 1970, HUD had to contract for their development. The criteria were developed by National Bureau of Standards (NBS) with some consultation services provided by a special Advisory Committee to the Department of Housing and Urban Development formed by the Technical Panel of the National Academies of Sciences and Engineering. The first volume of the "Guide Criteria for the Evaluation of Operation Breakthrough," dealing with multi-family high-rise structures, was delivered to HUD in January 1970. This and the subsequent three volumes (multi-family low rise, single-family detached, and single family attached) were thus presented to the housing system producers after they had prepared their proposals with reference to the model codes. And, as a result, some redesign of the systems was necessary to comply with the standards set forth in the Guide Criteria as required in the Phase I and II contracts.

The Guide Criteria differ from existing building codes in two respects. First, they are performance based and systems oriented as opposed to existing building codes, which are prescriptive in nature.

\footnote{A number of the proposals were based on systems already in operation and which, therefore, complied with existing codes and FHA Minimum Property Standards.}
and component or material oriented. In addition, The Guide Criteria
are broader in scope than most codes and address not only the public
health and safety of housing but also its livability and durability,
subjects of concern to mortgage lenders who are frequently guided in
their decisions by FHA’s Minimum Property Standards (MPS). However,
The Guide Criteria were not developed to dovetail precisely with the
MPS, which were themselves under review, primarily because the Break-
through management viewed the MPS as too minimal for housing units
designed for a broad range of economic and social groups. This
difference in standards caused problems and delays for the program
during the negotiations for FHA-insured mortgage financing for the
Phase II construction since the Breakthrough systems were designed
to meet criteria which the rest of HUD (FHA) did not acknowledge.

Perhaps the key problem with the Guide Criteria and the cause of
most of the delays associated with their introduction into the Break-
through program was that of interpretation and implementation. The
Guide Criteria were phrased in terms of performance language and a
number of the tests for compliance depended on new concepts or profes-
sional judgments. Thus their interpretation was more complex and less
uniform. The engineers and technicians at the National Bureau of
Standards who were trying to design the optimal criteria and associated
tests had one interpretation; the housing systems producers who were
trying to implement the criteria in their architectural specifications

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1 This is a direct consequence of the decision to demonstrate whatever
Breakthrough did with communities designed specifically to accommodate
such an income and racial mix.
and actual construction had a second interpretation; and the FHA underwriters who were trying to evaluate the long term marketability of units designed to these new (and possibly more costly) criteria had a third.

Not only did the Guide Criteria cause problems during the implementation of Breakthrough, they also complicated the evaluation of the program's results. It is difficult to test the effect of Breakthrough housing on the regulations and procedures in the prototype sites--i.e., determine the degree to which the temporary waivers obtained for the Breakthrough construction should be incorporated into permanent code revisions--because the Phase II Breakthrough units are designed to performance criteria whereas the local codes are couched in specification language. Furthermore, a number of experimental exceptions from the Guide Criteria were granted to the housing systems producers, making it difficult to identify the criteria to which the Phase II prototypes actually comply.

One important, positive byproduct of the development of the Guide Criteria was the shift in the testing industry toward standardized evaluation. The Department of Commerce developed uniform standards for evaluating testing laboratories on the basis of the Breakthrough-related work carried out by the National Bureau of Standards and the American National Standards Institute.

PARALLEL DEVELOPMENT STRATEGY; IMPLICATIONS FOR SYSTEM DESIGN

From the beginning of the program, it was evident that Operation Breakthrough was trying to do too much in too little time and that the program's ultimate success would require either pruning the objectives or expanding the time schedule (or both). A policy decision said the
time schedule stayed; the inclinations of the program managers were to retain and even broaden the complex set of goals. The solution to this conflict was theoretically obtained through the adoption of a parallel R&D management strategy in which work on a number of the program's components and related objectives was carried on simultaneously.

The success of such a strategy obviously depends on the characteristics of the program to which it is applied—the existence of objectives which can be disaggregated into enough components so that (1) the costs of a mistake in any one part are small relative to the costs of the entire program and (2) the relationships among the components are well defined and understood in advance so that they can be successfully reassembled at the program's conclusion. In addition, the management strategy must provide for a close and careful monitoring of those decisions which are made so that errors can be identified before they become too permanent and too costly to reverse and correct. This strategy for parallel development had been successfully used in the NASA space program, in which two members of the top-level Breakthrough management team had previously worked. But it is not clear whether the approach is equally applicable to a program which includes not only the construction and testing of hard products (houses) but also the design and implementation of a number of institutional arrangements by which those hard products are evaluated, financed, and used.

Breakthrough was split into divisions for technical operations (the design, evaluation, and construction of the prototype units), site planning, market aggregation, and financing. Although the simultaneous development of the site plans, housing system designs, and financial arrangements for
the Phase II construction may have bought Breakthrough some freedom in its time schedule, it seriously reduced the program's flexibility in other respects. And, as a result, the extra time was used up in redesigning the housing systems and reshuffling the systems across the sites in order to meet the financial commitments contained in mortgages arranged before the sites and systems had been completely designed and evaluated.

The Phase I contracts were designed to develop and test the innovations contained in the winning proposals to whatever degree necessary for their construction in Phase II and their subsequent commercial application (volume production) in Phase III. Neither HUD nor the HSPs assumed that all systems were free of technical problems. But the producers did expect to be given sufficient time during Phase I to work through whatever difficulties did arise with respect to either the technical feasibility of the system itself or the ability of the system to comply with the NBS evaluation criteria and tests. On the other hand, it was not expected that this development work would involve substantial amounts of time. All the systems utilized off-the-shelf technology, and a large number were modifications or extensions of systems already in commercial production. However, this view of Phase I did not foresee the introduction of the Guide Criteria into the producer design efforts, the subsequent delays and problems associated with their interpretation and implementation, and the consequent implication of these events on the design and development of the systems themselves.

Substantive changes were made in over half the housing systems in order to comply with the NBS evaluation and testing procedures. For

1Details of these changes are discussed in the description of the housing system producers contained in HUD, Feedback: Design and Development of Housing Systems, pp. 19-225.
some of the systems involved--Camci, General Electric, FCE-Dillon, Material Systems, and Scholz--the modifications could be incorporated in a relatively straightforward manner although they probably resulted in increased construction costs. For others, the changes were more serious and involved not only the system's inability to meet the evaluation standards but also the lack of time to modify and retest the component under consideration in order to preserve the integrity of the entire system as originally proposed. TRW was forced to produce its Fiber-Shell system using panels rather than mandrel-wrapped modules. National Homes abandoned its original proposal for a stackable high-rise building system using modules constructed from noncombustible materials in favor of a low rise, primarily panelized system (using conventional materials) that it was already producing. The innovative features in material and design of Christiana Western's system were completely eroded during Phase I. The off-the-shelf designs did not satisfy the Guide Criteria's space requirements, and the polyester-fiberglass wall finish and the utility systems did not meet the life safety (fire) criteria. Christiana's Breakthrough proposal had been based, however, on a system that was considered to be fully developed, tested, and proven. The heart of Femtom's proposal was a polymer adhesive which replaced the heavy nailing in the construction of its housing modules. However, the adhesive's long term structural viability could not be tested within the Phase I timetable. As a result, the adhesive and the rest of the original proposal were dropped in favor of a system based on more conventional and more expensive modular construction. Townland was the final system to

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1 The system was covered by a National FHA Bulletin, an ICBO Report (International Conference of Building Officials), and a Southern Building Conference Approval.
undergo major changes between its selection and actual construction in Phase II. It was impossible to implement the original design for "created land" platforms above ground level within the time and budget limitations of Phase I. The innovative features of the design were modified, as a result, to yield a more conventional version of Townland's supported land system.

When the originally proposed housing systems failed to meet the Breakthrough evaluation criteria, modifications were made which resulted in systems which were frequently more expensive and less innovative. This situation could have been avoided if those HSPs most severely affected had terminated their program participation at the end of Phase I. However, the site development and associated mortgage financing for Phase II had already been organized. And it was not, at that point, feasible to either (1) issue an RFP for a substitute system since there was not sufficient time to implement a Phase I contract for a new system or (2) reduce the size of the subdivisions since smaller developments would not generate sufficient income (through sales and rentals) to support the amenities which had been included in the site designs and mortgage values.
V. THE IMPLEMENTATION OF BREAKTHROUGH: PHASE II

CONTRACT NEGOTIATIONS

Despite the problems encountered by a number of the housing system producers in Phase I, 21 of the 22 firms entered into contracts for prototype construction in Phase II. The single exception was Stirling Homex, which was in bankruptcy. An additional change occurred with respect to Townland's Phase II units. These were eventually constructed by the Boeing Company, the developer for the King Country and Seattle sites, as a result of the financial difficulties and subsequent reorganization of the Townland consortium late in 1971.

Although the final contracts were signed between the site developers and the housing producers—yielding close to 40 rather than 21 contracts, the actual negotiations were carried out by the HUD central office in Washington. HUD negotiated a total production contract with each producer and then allocated the units to the various sites with respect to the research and demonstration aims of the project. Precisely what these aims were is not clear. The original program plan called for a six-month visitor program for each site as part of the evaluation process by which HUD would ultimately certify the systems. The planned implementation of this program influenced the kind of housing displayed on each site.\(^1\)

In addition, the producers expressed much interest in displaying their systems on the two Midwest sites, Kalamazoo and Indianapolis, which were seen to provide the best (i.e., generalizable) market test of the systems.\(^2\) As can be seen in Table 10, which gives the allocation of

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\(^1\) Subsequent funding cutbacks eliminated the visitor program on all but the Macon and Kalamazoo sites.

\(^2\) The assumption seemed to be: if it will sell in the Midwest, it will sell anywhere.
systems across sites, Kalamazoo, Indianapolis, and Macon contained the
greatest number of systems although not the greatest number of units.
Another frequently stated reason for the contract involvement of HUD is
that individually negotiated contracts between the HSPs and the developers
would not necessarily have led to an optimal number of units across all
sites for each producer. Optimality in this context refers to the amount
of total production which would make a factory economically viable. However,
according to the data in Table 10, only FCE-Dillon came close to producing
the equivalent of a volume-production run.

HUD's involvement in the contract negotiations may have been neces-
sary to protect the interests of both the housing system producer and
the federal taxpayer. There was no guarantee that a site developer
would not take advantage of the opportunity for financial obfuscation
and subsequent gain presented by a contract which he negotiated but
for which the federal government bore ultimate financial responsibility.
However, the negotiations and subsequent monitoring of over forty contracts
between the producers and the developers, 8 contracts between the developers
and HUD, and 9 more contracts between the site planners and HUD used up
a good deal of Breakthrough staff time. A simpler approach—for example,
negotiating a contract with a master developer to deliver a Phase II site
on a turnkey basis\textsuperscript{1}—might have been more realistic with respect to the
program's time and money budget and might have freed staff time for
other, evaluation-oriented tasks.

\textsuperscript{1}The standard HUD response to this suggestion is that it would have
been impossible to implement. In HUD's opinion, no developer/contractor
had the expertise in both construction and planning required by such
as approach.
### Table 10

**Allocation of Housing Systems to Phase II Prototype Sites**

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<th>Jersey City</th>
<th>New Jersey</th>
<th>Kalamazoo</th>
<th>Michigan</th>
<th>Macon</th>
<th>Georgia</th>
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Table 10—Continued

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</table>

| Total Number of Units Per Site | 295 | 486 | 245 | 287 | 518\(^b\) | 407 | 464 | 58 | 178 | 2938\(^b\) |
| Number of Systems Per Site    | 8   | 3   | 7   | 7   | 4\(^b\) | 4   | 5   | 1  | 4   | 40\(^b\)  |

\(^a\) Non-Breakthrough.

\(^b\) Includes 144 non-Breakthrough units and 1 non-Breakthrough system.
The contracts for Phase I were cost reimbursable, and there was an implicit promise on the part of HUD that the Phase II contracts to the HSPs would also be cost-plus. However, HUD's contracting authority for procurement activities did not permit this. The Phase II contracts were negotiated, therefore, on a fixed fee basis. Although this type of contract may have been appropriate for construction activity insofar as it provided incentives for the producers to keep costs down, it left HUD in the awkward and unfortunate position of being unable to acquire accurate cost data for the Phase II construction.

The housing system producers went ahead with Phase II under undesirable (from their point of view) contract terms for several reasons. First, Operation Breakthrough was deliberately being carried out with much publicity in both the national press and the building industry trade journals. For those firms which were new to the housing industry in general and its factory-produced segment in particular, this was an important free good, assuming the program and their performance were not disasters. Second, the association with HUD and NBS in Breakthrough gave an implicit imprimatur to those housing systems which were successfully demonstrated during the program, regardless of any official certification from HUD. Third, there appeared to be a pervasive belief in construction circles that Operation Breakthrough signaled the beginning of massive federal support for an industrialized housing industry, which would become the aerospace and defense contractor of the 1970s. And getting a piece of Breakthrough's Phase II and ultimately Phase III in the form of subsidy set asides, even if it meant some short term financial losses, was seen as the "foot-in-the-door" to what would be a profitable, long-term government-industry relationship.
SITE PLANNING AND DEVELOPMENT

The prototype site planners (PSPs) encountered a number of problems during their design work. Initially they were asked to design sites for housing systems about which they had very little information (a result of the parallel development strategy). Second, their contracts were of the fixed-fee variety; whereas architects traditionally work on a variable fee, determined as a percent of the project's total cost, basis. Third, and probably most troublesome, was the necessity for redesign. The original bids from the producers for the Phase II construction came in at $96 million for 3200 units; the final contracts were signed for $65 million and 2700 units. The reduction in cost was accomplished by cutting the total number of units and by concentrating production on the relatively less expensive systems. 1 Along with the elimination of 2 sites, this led to a series of changes in the allocation of units across the sites and resulting changes in the site designs to accommodate the shifts.

The site developers proved to be important to the success of the Phase II construction effort in two respects. First, those contractors which were local firms helped to get Breakthrough accepted by the site community. This usually involved a public relations effort to eliminate the "low-income federal housing" stigma initially attached to the Breakthrough developments in some sites. Second, the most successful developers were able to overcome the inertia inherent in a large, many-actor (including the federal government) project and expedite the actual

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1 In addition, the producers may have permitted HUD to negotiate them into paying for a greater portion of the factory start-up costs under the assumption that they would have first claim on the government subsidized housing market which they believed would be created in Phase III.
construction. Again, this tended to occur when the developer was a local firm and, therefore, knew how "to get things done" in the site community. Familiarity with federal government contracting procedures, as in the case of Boeing, also facilitated the construction process.

FINANCIAL ARRANGEMENTS; THE INVOLVEMENT OF FHA

The original program plan for Operation Breakthrough did not contain any explicit mechanism for financing the Phase II construction. When it became evident that the budget would not cover a construction program of the desired size, the decision was made to seek private mortgage financing backed by Federal Housing Administration (FHA) loan insurance. The negotiations with FHA, however, resulted in additional delays for the project. The reasons for the delays were complex and involved (1) the institutional organization of HUD, (2) the industry identification of FHA, and (3) the traditional FHA mortgage-insuring procedures.

The Department of Housing and Urban Development was formed in 1965 with the existing Housing and Home Finance Agency, which included FHA, as its nucleus. HHFA had never had a research budget of any consequence; and until Breakthrough was funded in 1969, neither did the Department. Not only was R&D a new activity for the federal government's housing agency, but, with the instigation of Operation Breakthrough, it also occupied a newly-legitimized position within the HUD bureaucracy. Romney elevated this policy research effort to a level which was on a par with the Office of Housing Production and Mortgage Credit, which included FHA, by creating the position of Assistant Secretary for Research and Technology.1

1The Office of Urban Technology and Research was the forerunner of the new office. It had possessed a narrower range of responsibilities and had exercised only limited independence.
Thus the career bureaucrats within the operating arm of the department were, to some extent, dislodged from their long-standing primacy with respect to federal government activities within the housing industry by a new office at the assistant-secretary level. Furthermore, this new office was responsible for HUD's (and the government's) first major housing research budget and for a new program with which HUD intended to revolutionize the existing housing industry.

FHA identified itself with this existing industry structure. The Assistant Secretary for Housing Production and Mortgage Credit during Romney's tenure at HUD was Eugene Gulledge, formerly president of the National Association of Home Builders. Gulledge was skeptical of both Breakthrough's means and ends, which he interpreted as an attempt to "federalize" residential construction in the United States by eliminating the free enterprise system in favor of an aerospace and defense type of government procurement. Furthermore, he believed that Operation Breakthrough's approach to the nation's housing problem was partially attributable to the failure, on the part of its program managers, to consult with members of the industry about their problems and their ideas for potential solutions.¹ And these problems were not how to build houses in factories but how to tap into the market, whose potential was illustrated by the growth of the mobile home industry, which would make such production profitable.

As a result of these attitudes, Gulledge initially did not encourage his staff in HUD's local FHA insuring offices to expedite the processing of the housing systems producers' applications for mortgage guarantees in Phase II or Phase III. Priority processing of Breakthrough projects did occur in several HUD field offices during Phase III, supported in part by a memorandum to the field signed by both Gulledge and Finger which directed that such procedures be adopted for Breakthrough applications.

¹This same criticism had been made of the CITF program.
However, in the opinion of both the housing system producers and the Breakthrough central office staff, local implementation of the Gulledge-Finger memo was sporadic and was usually instigated by central office inquiries rather than local office initiative. Such expedited processing would have been extremely useful. There were long queues for FHA loan guarantees, and a firm commitment to insure a multi-family dwelling on the part of a mortgage lender required an average of 14 to 16 months for processing. Furthermore, FHA's application forms and procedures were designed for traditional, stick-built housing and did not, therefore, reflect the realities of construction which utilized significant amounts of off-site, factory-based production—that is, the need to include a portion of the factor overhead plus any transportation costs from the factory to the site in the mortgageable value of the structure. Obtaining FHA-insured financing for multi-family developments required detailed plans and drawings. However, the mortgage financing for the Phase II prototype sites was arranged before the designs for either the sites or the housing systems were complete—a procedure bound to make even the most liberal FHA underwriter uneasy.

The problems in using existing FHA forms and procedures for Breakthrough housing were complicated by the fact that the Breakthrough units were built to satisfy the Guide Criteria, not the FHA-established Minimum Property Standards (MPS). The performance approach and language of the Guide Criteria were new to FHA underwriters. Also new were the tests for compliance, which involved either new concepts or depended on professional judgment. As a result, using the Guide Criteria to evaluate any building's eligibility for FHA mortgage insurance required more time and potentially more risk of error for the underwriter than using the specification-based MPS for which uniform, accepted interpretation was possible. In addition, several regulations in the Guide Criteria
established higher standards than those in FHA's MPS— for example, the safety and acoustic environment for single-family housing and the durability of materials used in both single- and multi-family construction. In the opinion of many FHA officials and many segments of the traditional building industry, the costs of compliance with these criteria might outweigh the benefits achieved, especially in situations in which there existed no established tests to determine whether the requirements had actually been met.  

Had the Guide Criteria been viewed by FHA and its traditional client, the small-builder segment of the industry, as just one more aspect of Operation Breakthrough whose validity and usefulness was to be experimentally determined during the course of the program, their implementation might not have led to the kinds of delays and problems which did arise. The industry at large, however, saw the Guide Criteria as something more. At the instigation of Assistant Secretary Gulledge, the FHA's Minimum Property Standards were themselves under review. And the prevalent feeling on the part of the industry, which the Breakthrough team did little to counteract, was that the Guide Criteria might completely replace the MPS with the stroke of George Romney's pen without any serious discussion of their technical problems and their destabilizing effects on construction practices. In Gulledge's opinion, Breakthrough's managers saw the performance-based Guide Criteria as an immediate solution rather than a gradual (and more appropriate, according to Gulledge) approach to increasing construction efficiency; and this reinforced his belief that Breakthrough represented an ill-informed and thus naive "solution" to the problems facing the building industry.

1These higher standards were established deliberately, due to the belief on the part of the Breakthrough management team that FHA's Minimum Property Standards were "too minimal."

Related to FHA and industry concern that Breakthrough housing systems were designed to construction standards which were not, in many instances, cost effective, was the opinion held by many of the same individuals that excessive amounts of attention and program funds were spent on the Phase II site designs. The concern was, again, the cost effectiveness (i.e., marketability) of design concepts which included amenities such as swimming pools and landscape features such as lakes and ponds in housing developments for low and moderate income families. The underlying opinion seemed to be that the Phase II developments did not provide a fair, "market" test of the housing systems displayed. The amenities of the site designs were considered so attractive, relative to what families at the target income level would otherwise be able to afford, that they could overshadow poor design and construction related to the dwellings themselves--features which, in more typical developments (those with few amenities) would hinder their marketability.\(^1\)

The philosophical and procedural problems for Operation Breakthrough which arose during its dealings with FHA were exacerbated by the Nixon administration's efforts to decentralize the federal bureaucracy. These reorganizations weakened the lines of authority within HUD between the central office, which held the majority of the Breakthrough program staff, and the area and local offices, where mortgage insurance was the primary HUD activity. And they occurred during the course of a program which was trying to accomplish the reverse of decentralization--a vertical and horizontal integration of the various components of the residential construction industry. As a result of the decentralization, the

\(^1\)This is the position taken in the National Academy report, pp. 47, 50. Introducing new site design concepts into the construction industry was, however, one of the secondary goals listed in the housing system RFP.
Breakthrough management team had to contend with regional and local HUD offices, which had their own bureaucracy, power structure, operating standards and procedures, and very little incentive to expedite the implementation of a federal program.

**PROTOTYPE CONSTRUCTION**

**Scheduling**

The construction on all nine prototype sites was undertaken simultaneously. Initially, the Breakthrough program staff believed that the construction on one site should be started first so that the experience and information gained there could be used to establish the procedures and thus facilitate the construction on the remaining eight sites. However, the policy decision to make the program national in scope and the potential political repercussions of selecting one site for special processing rendered such a procedure impossible. In addition there was the practical problem of selection—which site should be started first and why. The only feature of Breakthrough common to all sites was the HUD central office. In all other aspects of the program—site planner, developer, housing systems, HUD regional office staff, and local community—the sites were different.

Although work on all sites was begun at once, the Kalamazoo site, in Romney's home state of Michigan, was completed first (March 1972). This rapid completion can be attributed to the initiative displayed by the Kalamazoo developer in arranging the construction activities and handling problems as they arose. Also important was what appears, in retrospect, to have been a tacit agreement on the part of the Breakthrough staff to process the Kalamazoo paperwork first. However, whatever was learned in the Kalamazoo experience was formally lost to the rest of the program—with
the possible exception of the experience gained by individual HUD central staff members and the housing producers which built on other sites. Breakthrough was so far behind schedule by the winter of 1971-72 that there was no time available to digest the information from Kalamazoo and use it to revise whatever procedures were in operation on the other sites.

A second scheduling-related decision which affected the completion of the prototype developments was Romney's decision to advance the start date for the Phase III production. According to its own schedule, Operation Breakthrough was over 12 months late by mid 1971. Funding outbacks threatened the scope of the Phase II effort, ultimately costing the program 2 sites and 900 units, and might completely gut Phase III, which would not begin for another two years if the original sequence of the program phases was maintained. As a result, the housing system producers were permitted to mix Phase II and Phase III production provided that (1) the prototype construction for Phase II was already underway and would not be jeopardized by the simultaneous production of Phase III units, (2) the housing system was sufficiently advanced with respect to any remaining technical structural or production-related problems, and (3) the producer could actually market the units produced.

Thus Phases II and III became interdependent and, to some extent, competitive programs; and this further delayed the completion of Phase II. HUD's carrot for encouraging a speedy completion of the prototype construction had been the promise of priority access to federal rent and interest subsidies in Phase III. When both parts of the program operated at once, this incentive diminished in importance in direct proportion to the housing system producer's desire to market in Phase III.
Quality Assurance

As part of their Phase I contract tasks, the HSP's were required to develop and submit to HUD a program for maintaining quality production with respect to the off-site construction. These were reviewed by the Quality Assurance/Urban Planning Division of the Computer Sciences Corporation (CSC), which was under HUD contract to develop guideline criteria for the evaluation of the HSP quality assurance programs. These criteria were subsequently published as Volume V of the Guide Criteria, "Quality Assurance Program Provisions." According to CSC, it would be important for HUD to establish such criteria and then closely monitor subsequent HSP performance since the existing factory-built housing and, to some extent, mobile-home industries paid only minimal attention to quality assurance methods. Frequently, there was little operational difference between the off- and on-site techniques and associated quality control used by the industrialized housing producers. The individual with responsibility for quality assurance within the factory often reported to the production engineer whose goals involved the quantity of units produced rather than the quality of those units.

Despite this warning from CSC and the early attention paid at least on paper to quality assurance (QA), the QA program was not implemented effectively. According to the Technical Panel of the National Academy's Advisory Committee to HUD, "The prototype units examined did not appear to be of better quality than that found in housing constructed conventionally, and faulty construction processes were observed in the factories visited..."¹ New to residential construction and with a large number of other contract tasks to monitor, the

¹National Academy of Sciences, A Report on Operation Breakthrough, p. 46. The Advisory Committee visited the factories of three HSPs--Levitt, Material Systems, and TRW.
Breakthrough staff gave quality control a low priority under the assumption that active contract supervision in this area would not be necessary. Furthermore, given this initial uncertainty (despite the CSC report) about the need for a formal QA program, the Breakthrough staff was unwilling to contractually require the HSPs to spend the money necessary for its implementation. If the costs of such a program were, in fact, substantially greater than its benefits, its mistaken implementation would be reflected in the financial viability of the private firms involved. And the budget constraint operating on Breakthrough precluded HUD from simply reimbursing the HSPs for the costs of quality assurance programs set up in Phase II. In retrospect however, it is clear that for many of the systems any savings achieved by not monitoring quality within the factory were significantly outweighed by the need to hire extra on-site labor to correct structural deficiencies evident once the units arrived at the prototype sites.

HUD's unwillingness to saddle the HSPs with what it felt might be unnecessary costs is interesting since such risk-averse behavior was not evident during the Phase I evaluation and testing of the original designs. Although the immediate costs of the design modifications made to comply with the Guide Criteria were reimbursable under the Phase I contracts, the ultimate effect of such changes would be to increase the price of the Breakthrough housing marketed in Phase III. Evidence suggests that some of the safety and durability criteria may have been too stringent, resulting in housing systems which are not competitive with conventional construction.\footnote{See, for example, the opinion expressed by the Technical Panel of the National Academy's Advisory Committee to HUD in National Academy of Sciences, A Report on Operation Breakthrough, pp. 39-44.} The data to support such a conclusion are sketchy,
however. The Phase II contracts were fixed fee and thus did not require a complete cost accounting to HUD, and the Phase III cost data is considered proprietary.
VI. THE IMPLEMENTATION OF BREAKTHROUGH: PHASE III

MARKET AGGREGATION: HUD

In the original program plan for Operation Breakthrough's Phase III, the housing system producers would engage in volume production for aggregated markets. These markets would be developed according to the land inventories and priority schedules drawn up by state planning and finance agencies using Section 701a funding. However, due to administrative problems and misunderstandings within HUD, only $50,000 of the $1.5 million authorized for these state planning exercises had been released to Breakthrough by June 1971--$25,000 each to Rhode Island and Massachusetts. Furthermore, only three land inventories had been started--Rhode Island, Massachusetts, and California.

Although demand for the Section 701a funds initially exceeded the actual supply,¹ there is some question as to the longer term viability of the program. Two aspects effectively discouraged state agencies in the areas of public housing, finance and land planning from participating. First, control of the completed land inventory (within the state) would not reside with the initiating state-level agency but was to be turned over to HUD. And, second, the attempt to create such an inventory would likely lead to fraud and misrepresentation which public planning and housing finance agencies, by definition, sought to avoid. It was unlikely that private firms engaged in land development would give accurate estimates of their future demand for a property if these were to be telegraphed to HUD and to other developers.

Operation Breakthrough had more success in encouraging market aggregation through the adoption of state-wide codes for modular housing and other types

¹Had the entire $1.5 million been available to Operation Breakthrough, the central office staff planned to spend the entire amount in some 25 states.
of construction which require extensive off-site fabrication. The basic provision of such codes is that modules or other items approved by the state must be accepted by all local authorities within the state. In the opinion of Breakthrough's program managers, the construction and building code constraint to increased efficiency in residential construction was most easily attacked by action at the state level. There was no existing federal authority to permit the institution of a national building code; but there was already interest in State codes, exemplified by the formation of the National Conference of States on Building Codes and Standards in 1967. Using Romney's influence as a former governor, Breakthrough actively encouraged this interest. Program staff members drafted legislation for state-wide industrialized housing codes and spoke with legislators and other individuals to lobby for its passage. Before 1968, no states had such codes; by 1974, 31 states had enacted them. Reciprocal certification between states, however, has proceeded more slowly. Although it is difficult to attribute success in this area directly to Breakthrough, the circumstantial evidence in support of such a conclusion is nonetheless persuasive.

Much less progress was made toward permanently eliminating other factors which fragment housing markets such as local (as opposed to state) building regulations, zoning laws, transportation tariffs, and union agreements. Changes in these regulations were obtained for the Phase II construction. For example, local building code and zoning restrictions were waived for the Phase II sites; point-to-point tariff reductions were obtained for railroad transportation and highway transportation costs were stabilized;¹ and a large number of labor union agreements were signed which permitted individuals to cross jurisdictional lines in the Phase II factories and prototype sites. But in most instances, these

were specific, temporary waivers granted for the prototype site construction
with no intention of their being automatically continued into Phase III. The
emphasis of Operation Breakthrough had become Phase II, which was operating
simultaneously with Phase III and whose complexities engaged most of the avail-
able program staff time. Furthermore, Breakthrough had very little leverage in
Phase III since it did not own the housing units or developments constructed
in that part of the program.

Thus, by early 1971, it was evident that existing federal policy instru-
ments and programs were not capable of restructuring the operation of housing
markets conditioned by state and local institutions. Achieving market aggrega-
tion by federal actions would require sufficient time to design and implement
new instruments and new programs. But Operation Breakthrough was already nearly
a year behind its official schedule. The decision was made, therefore, to turn
over the primary responsibility for market aggregation in Phase III to the
housing systems producers. In order to facilitate this task and encourage the
manufacturers to actually enter the market, HUD gave the HSPs priority access
to Section 236 rent subsidy funds in amounts sufficient to cover 1000 housing
units per producer. In theory, these subsidy set-asides served two purposes:
(1) they provided the housing producer with a production run of sufficient size
to permit the construction of an efficiently-scaled factory, and (2) they gave
the HSP the time to develop his own marketing program for implementation once
the HUD subsidies were exhausted.

MARKET AGGREGATION: THE HOUSING SYSTEMS PRODUCERS

Of the 21 housing system producers who participated in Phase II,\(^1\) all but
four—Boise Cascade, C. E., Pantek, and Pemtom—planned to proceed to Phase III.
Of these, 14 actually built in Phase III, the three exceptions being Building

\(^1\)Stirling Homex, one of the original group of 22 HSPs, went bankrupt before
its Phase II construction had begun.
Systems, Shelley, and Townland. Approximately 25,500 Phase III units will ultimately be constructed in 150 developments in 36 states using the Section 236 Subsidy set asides. In addition, 1500 units have been built in Phase III using unsubsidized market rate financing. As of spring 1975, 12,000 of these units are completed and occupied; 10-11,000 are under construction; and the remainder are still in the planning stage. And several of the HSPs have marketed a total of 7000 units outside the Breakthrough program, most of which are still under development.

In order to achieve these results, the producers had to overcome several difficulties associated with marketing their systems in Phase III. A number of the producers were new to the housing market and thus had to learn a new set of institutional practices. Furthermore, all of the Breakthrough marketing was to be done on a direct sale basis. And this meant that the HSPs would have to operate outside the industry's traditional marketing network which relied on firms such as building materials suppliers to provide the interim construction financing. Finally, the Breakthrough manufacturers had to deal with the regulated market place, which involved both the federal government, through the FHA mortgage insurance and Section 236 rent subsidy programs, and state agencies—each of which had its own set of rules, regulations, and red tape.

Several factors had pushed the housing systems producers into the subsidized portion of the housing market. Construction costs had escalated nearly 30 percent since the initiation of Operation Breakthrough in 1969—a rise somewhat greater than that experienced by the prices of other consumer goods so that the real price of housing had also increased over the period. \(^1\) This increase in construction costs may have been accentuated in the case of the Breakthrough systems, which had undergone several redesign efforts in order to

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\(^1\) HUD, *Housing in the Seventies*, Chapter 8.
comply with the Phase I evaluation and testing. Furthermore, the high interest rates and shortages of funds for mortgage lending after 1973 led to an increase in the inventory of unsold houses and a rapid escalation in holding costs for builders and developers and thereby destroyed the speculative building part of the housing market. As a result, middle income people were unable to purchase new housing without some mortgage subsidy.

According to Breakthrough's original program plan, HUD had intended to certify the housing systems following the completion of Phase II. Such certification would have enhanced the marketability of the systems by implicitly guaranteeing their livability and durability and by permitting an expedited processing of applications for FHA mortgage guarantees for developments which used the Breakthrough systems. With certification, the applications could be routinely processed through the local FHA insuring offices rather than being reviewed on a project-by-project basis, a procedure which took an average of 12 to 16 months for a typical multifamily development. However, HUD later determined that it could not legally provide such certification. And, as a result, the HSPs were forced to enter the applications queue in the local FHA offices. The standard FHA review process took even longer for some of the Breakthrough projects in Phase III insofar as they were designed to meet the performance-based Guide Criteria which FHA did not officially acknowledge. For example, some of the rooms in the Breakthrough units were either too small or too large to comply with the regulations set forth in the Minimum Property Standards (MPS) used by FHA underwriters to determine the qualifications of a project for subsidized credit. In order to avoid further delays in an already overdue Phase III, the Breakthrough staff authorized, in the fall of 1972, the redesign of the systems being marketed in Phase III to accommodate local building codes and the MPS. However, in order to take advantage of this
increased design flexibility, the Breakthrough manufacturers had to weigh the long run marketing advantages against the short run costs of system redesign (which would eliminate many of the innovative features) and factory retooling.

This redesign did not, however, completely eliminate the problems which arose between the Breakthrough manufacturers and the FHA bureaucrats. The HSPs now had to prove that housing systems built according to the Guide Criteria and then redesigned to conform to the MPS did not cost more than comparable systems. And, in order to accomplish this task, the HSPs were forced to become the translators of Guide Criteria performance-related designs, factory-produced housing techniques, and MPS standards in order to prove to the local FHA underwriters that their units (1) could be built for the cost estimated, (2) would last, and (3) were marketable and would, in fact, be purchased.

The responsibility for facilitating the negotiations between the manufacturers and FHA fell to the two to three Breakthrough staff members located in each of HUD's regional offices. These individuals were not directly involved in the financial arrangements for the Phase III developments but did handle problems as they arose. The key to the successful and speedy resolution of such problems was the existence of a regional office administrator who supported the Breakthrough program and who would, therefore, exert bureaucratic pressure on the area and local FHA insuring offices to expedite the processing of the Breakthrough applications.

The most significant obstacle faced by producers wishing to market in Phase III was the imposition of a moratorium on HUD's Section 235 (home ownership) and Section 236 (rent) subsidy programs in January 1973. Although the original commitments of 1000 subsidy units per producer were honored, no further funds were allocated to these programs. As a result, those housing system producers that had geared their systems specifically to the MPS market were saddled with factory set-ups which produced housing units too costly to compete in the market without government subsidy.
VII. PROGRAM OUTCOMES AND IMPLICATIONS FOR FEDERAL DEMONSTRATION PROJECTS

PROGRAM OUTCOMES

The objectives of Operation Breakthrough which appeared in the housing system producer RFP outlines a broadly based attack on the entire mechanism for producing housing services. Although such an integrated systems approach to increased efficiency in residential construction was probably correct, it is difficult to determine, ex poste, precisely what the program accomplished insofar as the goals were stated in general terms and are, as a result, subject to varying interpretations. According to an Urban Institute report,

Because of the program's design, it will be impossible, in practice, ever to tell anything definitive about its effects on the nation's housing production, on the characteristics of the housing production and related industries, or on the institutional and attitudinal constraints to the use of industrialized housing production methods.¹

Furthermore, any evaluation of Breakthrough must contend with the fact that the U.S. housing industry has been severely depressed since 1973 in response to the shrinkage in the quantity of credit available for housing and the increase in its price (the rise in mortgage interest rates). This broad-based slowdown in construction activity makes it extremely difficult to determine the near-term impact of Operation Breakthrough, in terms of its technological and institutional goals,

¹Weidman et al., Summary of Initial Assessment and Evaluation Study Design for Operation Breakthrough, p. 2. The study contains a general discussion of the degree to which each RFP objective was obtained and lists a number of questions which need to be answered before a more detailed assessment of the program's accomplishments can be made.
on the housing industry. One should not blame the Breakthrough program itself for the poor track record of industrialized housing since 1973 insofar as all types of housing construction exhibited a substantial decline over this same period.

The following objectives were attained:

1. Houses were built, sold, and occupied in Phases II and III in a program run reasonably on budget and on time (in terms of its global schedule). Twenty-nine hundred units were built in the prototype, demonstration Phase II; and approximately 25,500 units will be completed in Phase III. The total cost of Phases I and II (design development and prototype construction) was $147.7 million and can be disaggregated as follows: net federal government cost, $72.2 million; financing by private and state lenders, $65.4 million; rents and sales, $8.1 million.

2. The houses were displayed within communities which were integrated racially and economically. In addition these community developments embodied the planned unit development design concept, in which a variety of housing types are used on a single site.

3. The Phase II housing units and developments exhibited a high degree of consumer acceptance. A 1974 survey of the respondents indicated that 90 percent of the respondents were satisfied with the dwelling units (60 percent were very satisfied), 92 percent were satisfied with the site features (56 percent were very satisfied), and 80 percent were satisfied with the site management (42 percent were very satisfied).†

4. A comprehensive set of performance-based evaluation and testing procedures have been created. Some aspects have been incorporated into FHA's minimum property standards, although they have not been adopted by local regulatory agencies. Some changes have also been made in testing procedures and standards for evaluating testing laboratories.

5. A majority of states have adopted statewide building codes, and a number of reciprocity agreements among the states have been made. The evidence that this can be attributed directly to Breakthrough is, however, circumstantial.

6. Several major companies became active in housing production for the first time, and some remain active. Of the 14 housing system producers that built in Phase III, 10 are still marketing domestically (4 are also marketing abroad), and one is marketing solely abroad. The relationship between HSP participation in Operation Breakthrough and success in the post-Breakthrough factory-produced housing market is difficult to determine, largely because of the non-Breakthrough related recession in residential construction activity since early 1973. According to some observers, the most successful of the manufacturers, primarily firms whose systems were being produced and sold before the program's inception in 1969, would have been successful without Operation Breakthrough. However, Breakthrough did contribute to an increased sophistication in the technology of these firms' housing systems and did provide them with an introduction to the low-income (i.e., subsidized) portion of the housing market.

7. A large number of cooperative labor agreements were signed during Phases II and III.

8. Transportation charges (point-to-point tariffs) for completed housing modules were reduced.

9. A few local developers were given experience with new approaches to housing. And some minority group subcontractors and workers were provided with new opportunities in the housing field.

10. State housing finance agencies have begun to engage in significant housing market aggregation activity in the subsidized, multi-family portion of the market. In order to lend, many of these agencies (especially in Massachusetts and Michigan) have had to induce the reorganization of demand and supply by all of the participants in the housing industry. Approximately 10,000 of the 25,500 units in Phase III were financed through these state-level agencies.

However, the following major program goal did not occur; at least in the short term:

1. Breakthrough did not directly stimulate significant innovation in housing production technology. The quality of the Breakthrough housing was not as high as expected, and the production costs of the Breakthrough systems were not appreciably lower than those for housing of comparable quality. On the other hand, the program did demonstrate the economic superiority of panelized or component systems relative to housing modules under prevailing transportation tariffs.
2. In addition, several of the housing producers involved in Operation Breakthrough have suffered substantial financial losses, not entirely unrelated to the program itself.

HUD published four Breakthrough-related reports as part of an information dissemination effort known as "Feedback"--Housing Systems Proposals for Operation Breakthrough, Feedback: Design and Development of Housing Systems, Feedback: A Compendium of Building Concepts, and Feedback: A Documentary of Transportation and Handling Systems. As indicated by the titles of these reports, they are primarily vehicles for a straightforward presentation of some of the mass of data generated during the program and do not subject this data to any formal evaluative analysis.¹

A substantial amount of additional information could be obtained from Operation Breakthrough. Of particular value would be a comparison of the Phase II and Phase III production and marketing experiences of those producers who participated in both. However, neither Phase III nor the post-construction experience in the Phase II prototype sites is being actively monitored by HUD largely due to the lack of interest on the part of the individuals who replaced Secretary Romney and Assistant Secretary Finger in January 1973 and a consequent lack of the additional program resources necessary to undertake such investigations.²

¹Of the four volumes, only the second--Design and Development of Housing Systems--goes beyond mere description to some analysis of the problems faced by the manufacturers in bringing their systems into production within the aegis of Operation Breakthrough. Although it details the experience of the 22 HSP's during Phases I and II, it does not attempt to synthesize the individual histories in order to determine why the problems arose and how they could have been avoided more expeditiously.

²Early in 1976, HUD did sign a contract with the Real Estate Research Corporation to evaluate Phase III.
IMPLICATIONS FOR FEDERAL DEMONSTRATION PROJECTS

The lessons for federally funded demonstration projects and programs which can be gleaned from this analysis of Operation Breakthrough fall primarily in the area of program implementation.

1. The Relationship of Goals to Management. The rational approach to program analysis assumes that the predetermined goals of a project will dictate the logic of its implementation. For Operation Breakthrough, however, the reverse was true. To a significant degree, the methods by which the program was managed determined which goals were emphasized and subsequently achieved. This confused connection between goals and management was further confounded by the imposition of a number of policy-level decisions which reduced the program's flexibility and thereby constrained its ability to achieve those institutional changes originally listed as the program's most important goals.

Implementation strategy can be determined most readily by a project's goals when these goals are themselves internally consistent in terms of both the logic of the problem to which the program is addressed and the time and budget available for seeking a solution. Breakthrough's original program design included market aggregation as a significant goal, which, according to the discussion in Section II, was the limiting factor with respect to increased construction efficiency. However, the degree to which this would actually be the focus of the program depended on the budget allocations for Phases II and III--
research versus demonstration, hard products versus institutional change. And, as was shown above, policy concerns drove Breakthrough in the direction of Phase II, leaving Phase III (as originally planned) and the difficult institutional issues largely untouched and unresolved.

2. **Policy versus Program Decisions.** Policy-level decisions include those made at the level of department secretary, agency head, or White House administration; whereas program-level decisions occur at the level of the demonstration project or agency program to which it belongs. The outcome of the demonstration may depend importantly on the degree to which these two levels of decisionmaking are mutually supportive or conflicting. This distinction may have its greatest operational significance with respect to a demonstration project's time and budget allocations. Policy decisions which impose a tight time schedule and/or a strict budget ceiling may limit the flexibility of the project and, therefore, inhibit the ability of the project managers to respond effectively to problems encountered in implementing the demonstration's program plan.

The interaction between policy and program decisions is complex, and it is difficult to describe the "proper" role for each. Federally-sponsored research and development activities in the civilian sector are, by definition, carried out in a political environment. The ideas for demonstration projects and other applied R&D programs are frequently crystallized by concern with social or economic problems which is articulated
through the political apparatus. In addition, securing a successful conclusion to a demonstration project—the diffusion of the hardware-related technology or the institutionalization of changes in industry behavior and operation—may require the support of policy-level decisions outside the jurisdiction of the project or program managers.

For example, the continued diffusion and operation of the technical and institutional changes sought by the Operation Breakthrough program staff probably required some combination of the following: (1) a continued HUD-sponsored push on state governments to adopt statewide industrialized housing codes which would be reciprocal among states and would eventually be based on performance rather than specification standards; (2) continuation and possible expansion of the federal subsidy program for rent and home ownership by low and moderate income families; and (3) the insulation of the residential construction market from the effects of macroeconomic policies (monetary-interest rate policies) implemented for other, nonhousing purposes. The problems for demonstration project managers of obtaining new or continued policy support at the conclusion of the project will be difficult if, as is frequently the case, the administration personnel and other high-level department or agency officials who marshalled support for the original project are no longer in office.

3. Intragovernment Implementation. The relationship between project goals and management can be blurred still further by problems which may occur with respect to the implementation of the project within the bureaucratic apparatus of the federal government, as opposed to the problems of implementation with respect to the actual target audience of the demonstration, whether this is the private sector or a state or local government agency. The success of the demonstration
may hinge significantly on the degree to which the problems of intragovernment implementation can be minimized so that the resources (especially staff time) available to the project can be focused on the target audience.

These two types of implementation are not, however, as independent as this description would imply, particularly in a situation in which institutional change is an important aspect (in terms of both cause and effect) of the project's success. When the target audience is an established industry, client/advocate relationships may already be established between the components of the industry and agencies within the government other than the one directly responsible for running the demonstration. Achieving the diffusion of a new technology which threatens the institutional status quo of the industry may precipitate concomitant changes in the bureaucratic status of these other agencies. And successful implementation vis-à-vis the target industry audience may require implementation efforts with regard to this related government audience so that these agencies, even though not directly involved in the management of the demonstration project, will not serve as a hindrance to its completion. The cost, in staff time, of engaging in such bureaucratic institution-building at the start of a demonstration project may appear to outweigh the benefits, given the probability that the efforts may not be necessary. Failure to do so, however, may lead to other more serious delays later in the program. Agencies with no particular stake in the outcome of a demonstration may be unwilling to either sign-off on or expedite the processing of those aspects of the project which fall within their administrative bailiwick.

The existence of such intragovernmental implementation problems
which remain largely unresolved over the course of a demonstration
has important implications for the target audience implementation effort.
The industrial sector or the state or local government agency which
is the target audience for the demonstration may be unwilling (other
things being equal) to undertake action which is potentially destabilizing
and risky in order to meet a "national goal" or solve a "national
problem" if the federal government can't agree within itself on either
the goal or the problem or the method by which it is to be achieved
or eliminated.

For Operation Breakthrough, the problem of intragovernment imple-
mentation arose with respect to the operating arm of HUD—the Office of
Housing Production and Mortgage Credit (HPMC), which included the Federal
Housing Agency (FHA) and its mortgage insuring activities. The policy
level decisions to run the program under a tight budget while con-
structing the maximum (3000) rather than the minimum (1000) number
of prototypes included in the original program plan led to the program-
level decision to use private mortgage money to finance Phase II con-
struction. Given the experimental and innovative aspects of the proto-
type developments, this financing would be easier to acquire—the risks
to the mortgage lender would be reduced—if FHA insured the mortgages.
However, for reasons discussed in detail above, FHA did not jump on
the Breakthrough bandwagon with much enthusiasm. And the administrative
delays involved in obtaining the mortgage guarantees for the Phase II
and, eventually, Phase III construction cost the project both time
and money and, as a result of the budget constraint, led to the
elimination of a number of the project's non-construction components.
4. Program Evaluation. The problem for evaluation is to relate the treatments attempted by the demonstration project to the outcomes observed. The most desirable evaluation is one which can conclude that the project succeeded or failed, assuming one can define success or failure, because of the causal connection between the treatment variable, such as aggregated markets, and the project outcome, such as a more efficient (lower cost) production of houses. However, without a controlled, experimental environment, it will be difficult to definitively trace and establish such cause and effect linkages.

The presence of confounding effects will be particularly troublesome for programs, such as Operation Breakthrough, which contained a number of interdependent goals of parallel importance. Even if the available time and dollar budgets permit the program managers to maximize the achievement of all goals in a large-scale, simultaneous or sequential program plan, determining what caused what in such a multivariate (in terms of both treatments and outcomes) project will be difficult, if not impossible. And programs which take a "systems approach" to problems whose solution implicitly requires a change in the institutionalized system itself may be seduced into moving on all fronts at once even without the necessary time and dollars.

Furthermore, the lack of a sufficiently long time period in which to complete the project may push the project managers to adopt a strategy in which a number of the projects components are treated simultaneously, rather than sequentially according to the traditional linear model of the R&D process. The success of such a parallel management strategy depends on the ability to develop a logical plan for the complete project and then disaggregate the project into enough components so that (1) the
relationships among the components are well-defined and (2) the costs of making an error in any one component—the time and dollars required for any redesign when the entire project is put together—are small in relation to the resources devoted to the project as a whole. Breakthrough's managers used this parallel development strategy for both the institutional and hardware related aspects of the program. However, the intervention of several policy decisions and intragovernment problems limited the flexibility necessary to make such a strategy a success on all fronts. And, as a result, the simultaneous operation of a number of ultimately conflicting tactics made any ex post evaluation of the project within a cause-and-effect paradigm impossible.¹

This discussion of the "implementation problem" has brought us full circle from an analysis of the relationship between a project's goals and management to a discussion of the problems associated with its evaluation—problems which can arise as a result of the particular strategy used to implement and achieve the original goals. The implication of this circularity for analyses of demonstration projects is that the process by which the projects are created, planned, implemented, and evaluated does not necessarily fit the "linear" model of research and development, in which the information generated in step 1 of a project is completely digested and assimilated before proceeding to step 2. Nor does the process fit neatly into a conceptual framework which sees the demonstration as an activity which produces information subject to a variety of political and other institutional constraints. The politics of research and development are an important positive, as well as negative, influence on the outcome of a demonstration. And part of the art—

¹Regardless of whether rigorous, experimental procedures had been included in the program.
opposed to the science, which is implied by the information model--of
demonstration project management is the ability to identify the political
issues earlier in the project, discouraging those which constrain and
cultivating those which support and promote the project's successful
completion.
PERSONAL RAPID TRANSIT SYSTEM

by

Leland L. Johnson
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I. THE POTENTIAL ROLE OF PERSONAL RAPID TRANSIT

THE DECLINE OF PUBLIC TRANSIT

Despite strenuous efforts to maintain and further develop public transit, the private automobile continues to play the dominant role in urban transportation. During the decade 1960-1970 urban automobile traffic increased 74 percent in miles, while bus dropped 26 percent, and rail 8 percent. The taxicab, offering a service comparable to the automobile in terms of speed, comfort, convenience, and privacy, also enjoyed an increase in passenger miles by 31 percent during the 1960s. Today train, bus, and streetcar services combined comprise only about 5 percent of total urban trip miles. [Ref. 9, pp. 1-2]

Operating on fixed routes and schedules, public transit is severely handicapped in competing with the automobile, especially where pairs of origins and destinations are scattered widely around an urban area, as in Los Angeles. Typically, the user must walk or ride to the nearest bus stop or terminal, then take a vehicle that stops numerous times along the route, then be dropped still blocks or miles from his ultimate destination. Under these circumstances, and despite traffic congestion and parking problems, the public overwhelmingly prefers the automobile.

THE USE OF PRT

Much attention has been devoted to assessing the prospects of tapping new technology to make public transportation service competitive with the automobile, thereby reducing air pollution and traffic congestion, and conserving use of energy. Personal rapid transit has attracted interest in recent years as a promising possibility. PRT involves use of small remotely controlled vehicles operating on elevated guideways, as illustrated in Fig. 1. With a grid of such automated guideways, and numerous off-line small stations, an individual could obtain on demand a vehicle at a nearby station, and with use of a computer-based command-and-control system be routed through the grid to a station near his ultimate destination. With demand access and little waiting time, direct routing
Fig. 1 — Photomontage of Possible Personal Rapid Transit Installation in Downtown Los Angeles
to the other station without intermediate stops, the comfort of
electric propulsion, and the privacy of not sharing the vehicle
with strangers, PRT could approach the characteristics of the auto-
mobile that are clearly so highly valued by the American public.

Moreover, PRT, providing good downtown area coverage, can sub-
stantially strengthen the viability of conventional line-haul routes
served by buses, trams, and subways. One of the most serious problems
with today's line-haul service is that it drops the rider still some
distance from his ultimate destination. By having to switch modes, and
suffering the low speeds of public transportation in downtown traffic,
the traveler frequently opts for taking an automobile the whole distance.
With coverage of the downtown area afforded by PRT, however, including
stations close to ultimate destinations, stronger encouragement will be lent
to using existing line-haul facilities with traffic feeding into PRT stations
on the fringe of the downtown area. Alternatively, fringe parking
lots around the downtown area would afford the opportunity for those
who prefer to drive to park their cars away from the downtown congest-
tion and continue the rest of the way on PRT.

Once PRT covers the downtown urban area, it may be extended into
outlying areas to provide line-haul service. Thus, in a longer term,
the traveler might be able to board a PRT vehicle near his home in
the morning and travel all the way downtown to a selected destination
close to the office.

THE TECHNOLOGY

There are a number of critical factors relating to PRT technology.
First, as suggested in Fig. 1, the guideways must be small in order that
their capital cost be kept low (a critical factor since many miles of
guideway would be involved in a downtown grid system), and in order that
they curve around buildings and fit into space above existing sidewalks
and streets to obviate needs for demolition and land acquisition.

Second, if individuals are to be taken quickly from their origins
to destinations on demand, they must use small vehicles carrying no
more than three or four passengers. However, this service would in-
volve very short headways (the time required for two cars to pass a
given point) in order to ensure sufficient overall capacity during peak traffic periods. That is, vehicles carrying an average of 2 passengers must have one-tenth of the headway of vehicles carrying on an average 20 passengers for a given overall capacity. Previous studies, simulating conditions in major cities, show that under a range of reasonable assumptions headways must be reduced to less than a second. To obtain fractional-second headways requires going to a different braking system than conventional ones working through rubber tires on concrete guideways or on steel wheels running on rails. The most promising possibility is using a linear induction motor, or a pulsed d.c. motor, whose design essentially involves placing the motor's magnets along the walls of the guideway to provide both propulsion and, with reversal of current, direct braking. Linear induction motors have not yet been used operationally in public transportation, but are involved in experiments in both the United States and abroad in test-bed applications, while the pulsed d.c. motor is at an earlier stage of development. [9, pp. 12-16]

Third, it is critically important that the computer-based command-and-control system operate reliably and be supplemented by adequate fail-safe mechanisms. If individual cars are to have fractional-second headways while traveling at 30 miles an hour with individual routing, the vehicle switching system, the vehicle position indicators, and the rest of the command-and-control system will have to work very well to avoid mishaps.

To take one example, suppose one car loses power and begins to decelerate. Vehicle position sensors along the guideway would immediately send information back to the computer showing the position of the car and the rate of its deceleration. The computer, having simultaneous information about the speed and positions of other vehicles, would relay orders to them to slow down at a sufficiently fast rate to avoid collision. Orders would also be sent to the car behind to push the disabled vehicle to the nearest off-line station or maintenance depot. Other cars would be rerouted to avoid the congestion on this portion of the guideway. After the guideway is clear, commands would be sent
to cars behind to resume normal travel.

As another example, a car leaving a station would have to be merged into the main-line traffic, which would involve sensing its position, controlling its rate of acceleration, combining this information with that regarding the position of other cars and their speed, and working out a maneuver to bring the car up to proper speed and merge it into a slot among the others. Design of such a command-and-control system and the associated computer software is not an easy task, as we shall see in the Morgantown case below.

In order to maintain a satisfactory level of system reliability, the mean time to failure of the individual vehicle is a critical consideration. For a given mean time to failure of the vehicle, the probability of a vehicle failure somewhere on the system during a given time interval varies directly with the number of vehicles on the system. The more frequently a vehicle failure occurs, the more frequent is the shutdown of a section or all of the system until the guideway is cleared. Unless provisions are made for quickly pushing the vehicle off the main line, it is easy to imagine a situation where, with thousands of vehicles covering a major metropolitan area, system interruptions would be frequent and time delays intolerably high.

Of course, one can back away from such stringent requirements by simply going to larger cars, say to 12-20 passenger capacity. This permits longer headways, perhaps 10 to 15 seconds, so that conventional brakes, working through wheels on guideways, can be used in combination with conventional electric motors. With a given mean-time-to-failure system reliability rises, and less strenuous demands are placed on the command-and-control system.

However, a price must be paid for going to larger cars. Passengers must share individual vehicles, which raises questions of the willingness of people to travel in unattended vehicles with strangers (analogous to the elevator problem today). Second, with individuals sharing the cars, it may not be possible to route the car directly from the individual passenger's origination point to his chosen destination, except perhaps in peak periods where travelers going to common destinations can more easily be grouped together. Also, with larger cars the
the guideway would need be increased in size so that it could no longer be built solely over existing sidewalks and roads. In addition to the expense of acquiring land, the system would be more visually intrusive. With larger guideways and the requirements for larger stations to accommodate the groups of passengers congregating at common points, a coarser grid would be designed to reduce the total number of miles of guideway, and stations would be farther from origination and destination points. Thus, as we go to larger cars, involving group transit or GRT, the level of flexibility, speed, and privacy declines; and as they do, the competitive position of the system declines relative to the automobile. As we move yet to larger vehicles, we get closer to a tram system, or a subway system, where the number of passengers per vehicle becomes very large, headways long, perhaps numbered in minutes, and the flexibility discussed above further compromised.

All in all, if the technology can be satisfactorily developed, PRT may be an attractive alternative to conventional public transit systems, both in terms of cost and in public acceptance. Table 1, disclosing figures estimated in mid-1973, shows that for "high capacity PRT" consisting of 4-seat vehicles and 1/2-second headways, the capacity could be quite large relative even to the Washington Metro system, and at a substantially lower cost measured in dollars per lane mile per seat per hour.

Table 1
CAPITAL COST COMPARISON BETWEEN PRT AND RAPID RAIL (MID-1973)

<table>
<thead>
<tr>
<th>System</th>
<th>Capacity (seats per lane hour)</th>
<th>Cost (millions per lane hour)</th>
<th>Cost (dollars per lane mile per seat per hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washington Metro</td>
<td>19,500</td>
<td>15.2</td>
<td>780</td>
</tr>
<tr>
<td>(648 seat trains, 120 s headways)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dallas/Ft. Worth &quot;Air-trans&quot; PRT</td>
<td>3,200</td>
<td>2.6</td>
<td>812</td>
</tr>
<tr>
<td>(16 seat vehicles, 18 s headways)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planned PRT development</td>
<td>14,400</td>
<td>4.0</td>
<td>360</td>
</tr>
<tr>
<td>(12 seat vehicles, 3 s headways)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-capacity PRT</td>
<td>28,800</td>
<td>6.0</td>
<td>208</td>
</tr>
<tr>
<td>(4 seat vehicles, 1/2 s headways)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SOURCE: Ref. 23, p. 876.
GENERAL UNCERTAINTIES

We face a number of major uncertainties with respect to PRT:

Safety and reliability. Development of advanced command-and-control systems combined with mechanical emergency devices and non-conventional motors for both traction and braking will be critically important in moving to fractional-second headways required of high capacity, small vehicle systems. Development of vehicles with adequately high mean time to failure and modes for quickly moving disabled vehicles off the main-line guideway will be required.

Cost of guideways. Because of the many miles of guideway to cover adequately a central business district and the need for small and widely scattered stations to provide flexibility comparable to that of the automobile, cost per mile is a critical variable. Ideally, with small vehicles the guideways could be constructed of easily assembled prefabricated materials. At the other extreme, concrete steel-reinforced construction would be custom built for the particular installation. Much depends upon the size of the vehicles. According to one source, guideway costs increase roughly by the square of vehicle weight within the range of weights and costs relevant here.

Cost of vehicles. Because of the need for hundreds or thousands of vehicles in a PRT system of the sort in Table 1 above, the cost per unit plays an important role. Partly because the linear induction motor technology is not yet developed, nor are other on-board components such as the computer and auxiliary controls, the cost of manufacturing these small cars remains a major uncertainty.

Operating and maintenance costs. A fundamental potential advantage of PRT is that it substitutes capital for labor. One of the reasons why public transit systems are in so much financial trouble today is that the cost of labor, especially that of drivers, is very high. This is particularly a problem when the system faces two peak periods of traffic per day, but must pay drivers for a full day. In contrast, an automated system can operate 24 hours a day without this burden. However, the level of operating and maintenance cost is yet to be determined.
The reliability of the automated system, the costs of the relatively highly paid and highly skilled personnel required to maintain it, and a host of other considerations are subject to large uncertainty. 

**Institutional impact.** By substituting capital for labor and integrating a PRT system into a larger system of public transit, a number of institutional problems arise. What will be the reaction of labor unions if PRT is substituted for some portion of bus routes and the number of drivers is reduced? To what extent must public transit agencies change their internal organization and operating procedures to satisfactorily integrate PRT into the rest of the system so that users have satisfactory access to both (for example, the rider using a light rail system, such as BART, for the line-haul and easily transferring to a PRT system downtown). The coordination of schedules, operating procedures, fare structures, and other aspects may require substantial changes in public transit organizational procedures that are yet not well known. 

**Environmental impact.** Some have said that PRT would be aesthetically unattractive if large guideways are running all over a central business district. The vision here is something like the Third Avenue El, which contributed to deteriorating conditions along New York's Third Avenue. Clearly, much depends upon how small the guideways are. If they really could be built as simply as those shown in Fig. 1 above so that trees would not need be toppled, buildings demolished, and special rights of way established, then the problem would not be serious. But, as mentioned above, this aspect remains in doubt. In contrast, the contribution of PRT to reductions in noise, congestion, and air pollution can easily be appreciated if the service does become an effective alternative to the automobile.

**Demand by the public.** Last, and probably most important, is the uncertainty about the demand for PRT service. If PRT has the flexibility of service, speed and comfort, as mentioned above, will these factors together be sufficient to induce people to move out of their automobiles? If larger vehicles are built of the 12- to 20-passenger variety, as
a way of reducing the requirements for technological advance, will people be willing to share automated cars with strangers, and will reductions in speed and flexibility constitute a major deterrent to use? More generally, PRT represents an enormous capital investment. It can be justified only if there is a substantial switch of patronage from automobiles to PRT. One of the problems here, as in so many other cases in public transportation, is that a new system (such as BART) achieves its patronage largely at the expense of other public transportation systems rather than inducing people to switch from their automobiles. Disappointingly, new technologies have not affected overall modal splits to a significant extent. The question remains whether the additional advantages of PRT would be sufficient, for the first time, to have a major impact on modal split.
II. THE MORGANTOWN PRT DEMONSTRATION PROJECT

Hemmed in by hills along the narrow Monongahela River Valley, Morgantown suffers particularly severe transportation problems. In addition to the city's 29,000 population, the student body of West Virginia University, numbering 22,000, is spread among three campuses approximately 1 1/2 miles apart. With the winding and congested routes connecting the three campuses, students face difficulties in getting from one class to another. The University owns or leases 16 buses to handle approximately 12,000 passenger trips on a regular day schedule which involves five class changes. In addition, a large number of students use their own automobiles, estimated at about 6,000 to 7,000, further adding to traffic congestion.

THE ALDEN PROPOSAL

With its acute transportation problem, the University has been concerned about the possibilities of employing advanced technology to provide rapid and convenient transportation. Because UMTA was interested in evaluating the use of PRT for widespread application, it made a grant of $153,500 to the University in 1969 for a feasibility study of PRT systems in the Morgantown environment. This work culminated in a proposal by the Alden Self-Transit Systems Corporation for a 3.6-mile PRT system illustrated in Figs. 2 and 3.* Based on the Alden proposal, the University estimated the cost of a six-station system with 3.6 guideway miles and 90 vehicles (each carrying from four to six passengers) at about $18 million, with $13.5 million estimated as the federal share. In August 1970 the West Virginia Board of Regents, on behalf of the University, submitted a capital grant application to UMTA for the $13.5 million of the estimated $18 million needed to design, construct, and demonstrate the Alden PRT system. The Board's objectives were to:

1. Demonstrate the feasibility of a new transportation concept for the immediate needs of a mid-sized urban community or major activity center, and

*Fig. 3 shows the system as actually constructed with the solid line connecting three stations and the dotted line connecting three others along a route yet to be built.
ALDEN TRANSPORT SYSTEM FOR WEST VIRGINIA UNIVERSITY

SOURCE:  Ref. 1, p. iii.

Fig. 2--Downtown Campus Installation
SOURCE: Frank E. Lo Presti, "First U.S. Center-City People Mover Debuts in Morgantown, W. Va." Reprinted with permission from the November 1972 issue of CIVIL ENGINEERING--ASCE, official monthly publication of the American Society of Civil Engineers.

Fig. 3--Morgantown PRT System
2. Design, develop, test, and introduce into passenger service a PRT system that would solve the University's and Morgantown's present and future transportation needs. [27, p. 10]

To demonstrate the utility of this new technology, Morgantown was a particularly favorable site in the eyes of some because:

a. It would have a built-in ridership to ensure that the system would be used;
b. Morgantown's uneven terrain would provide useful information on design and construction requirements for the steep slopes;
c. Traffic has more peaks than in a regular two-peak community with the five class changes per day in Morgantown, thereby spreading the traffic load over a larger portion of the day;
d. Alden had already completed a feasibility study directed specifically to the needs and characteristics of Morgantown;
e. There was close cooperation among city, county, and state agencies in working out plans to be presented to the Department of Transportation.

The request came at a favorable time in that there was great interest in the aerospace industry to enter civilian-oriented activities, particularly in the rapid transit field, where it was widely felt that advanced technology, including that previously developed by aerospace companies, would be applicable.

In addition, political pressures were brought to bear such that in September 1970 the Secretary of Transportation announced that a public demonstration of the system would be made in October 1972—just a month before the presidential election. According to a General Accounting Office report, "UMTA officials accepted this goal and believed that the scheduled demonstration could be met, although they had not selected the system manager, defined the system's requirements, nor designed a development plan." [27, p. 39]
Table 2 illustrates the very tight project schedule that would have
to be followed if a prototype demonstration were to be made in October
1972, shown by the solid triangle in Table 2. Major systems contracts
would have to be awarded in mid-1971, only a few months after subsystem
functional requirements were completed and the route made final. The
prototype guideway and stations would need be completed within a year
of the time construction was to begin.

DEVELOPMENT OF THE SYSTEM

In September 1971 UMTA entered into a contract with the West Virginia
Board of Regents. Because of the time pressures imposed by the October
1972 deadline, a selection of prime contractor was made without normal
competitive bidding. JPL was assigned that task. Its early judgment
was that Alden did not have sufficient capability to justify a sole source
award. Therefore, in a competition involving a number of bidders, Boeing
and Alden together were awarded the contract for developing the vehicles,
Bendix, the task of designing the computer software and command-and-
control system, and Frederick R. Harris, Inc., the task of designing and
building the guideway system.

It was clear that the earlier $13.5 million figure was unrealistically
low, since it was not based on hard engineering data or cost analysis.*
In April 1971 JPL estimated the cost at $37.1 million—a figure that was
so high that the system was cut back from six stations to three, the
number of guideway miles cut back from 3.6 to 2.2, and the number of ve-

ciles reduced from 100 to 15, for a total new estimated cost of $23.4
million. UMTA reasoned that once the system was demonstrated in the
three-station mode, the University could apply to UMTA for a capital
grant (with 20 percent local cost sharing) to expand the system to the
original six-station concept. The reduced three-station system was
designated as Phase I, and the expanded or six-station system (including
the dashed route in Fig. 3) was designated as Phase II.

* According to the testimony of Mr. Frank Herringer, head of
UMTA, before a congressional subcommittee: "I did talk with UMTA people
and learned enough about the history to understand that it is dignify-
ing the $13.5 million to call it an estimate. It really wasn't what we
would consider a good construction, engineering, soundly based estimate."
[26, p. 657]
### Table 2
ESTIMATE AS OF EARLY 1971

#### MORGANTOWN PROJECT SCHEDULE

<table>
<thead>
<tr>
<th>DETAIL</th>
<th>CALENDAR YEARS</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Requirements and Constraints Approved</td>
<td></td>
</tr>
<tr>
<td>Route Finalized</td>
<td></td>
</tr>
<tr>
<td>Subsystem Functional Requirements Completed</td>
<td></td>
</tr>
<tr>
<td>On-Site Construction Begins</td>
<td></td>
</tr>
<tr>
<td>Major System Contracts Awarded</td>
<td></td>
</tr>
<tr>
<td>Subsystem Design Specifications Completed</td>
<td></td>
</tr>
<tr>
<td>System Design/Analysis Completed</td>
<td></td>
</tr>
<tr>
<td>Subsystem Test Completed</td>
<td></td>
</tr>
<tr>
<td>Complete Prototype Vehicle Delivered at Morgantown</td>
<td></td>
</tr>
<tr>
<td>Prototype Guideway and Stations Completed</td>
<td></td>
</tr>
<tr>
<td>Prototype System Test Completed</td>
<td></td>
</tr>
<tr>
<td>Prototype Demonstration Begins</td>
<td></td>
</tr>
<tr>
<td>Production Vehicles Delivered</td>
<td></td>
</tr>
<tr>
<td>System Functional Tests Completed</td>
<td></td>
</tr>
<tr>
<td>Joint Acceptance Tests Completed and Passenger Service Begins</td>
<td></td>
</tr>
<tr>
<td>System Demonstration and Evaluation Program Completed</td>
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</table>

**SOURCE:** Ref. 22, p. 457.
During this same time, JPL and the federal government failed to reach accord on a final contract. Negotiations broke down and in August 1971, after a selection process involving two bidders, Boeing was named as prime contractor to replace JPL. Boeing's initial cost estimate was $27.4 million—roughly the same as JPL's—but this figure was still based on an incomplete design system definition. When firm bids were received for construction of ground facilities and other items, the estimate for Phase I rose to about $40 million.

As a consequence of these mounting costs, Phase I was divided into two parts, IA and IB. IA encompassed the construction of the 2.2 miles of guideway and the testing of five vehicles to demonstrate technical feasibility—the phase that had the deadline of October 1972 for first prototype testing as part of an official dedication ceremony. The rest of Phase IA was completed in 1973. Phase IB includes an additional 40 vehicles and such items as fare collection, guideway heating, station communications and control equipment, operational computer software for a fleet of vehicles and other items in order to demonstrate the system in revenue service. After completion of Phase IB the system is to be turned over to the University, probably during the summer of 1975.

With the reduction of the number of vehicles in Phase IA to five, and with other cuts the cost of Phase IA amounted to $43.7 million. In contrast to an estimate of $52 million made in April 1972 for completion of the three-station system (including both Phases IA and IB), the cost at completion will run to about $64 million because of the numerous hardware, construction, and testing modifications, and schedule slippages. A history of cost changes, broken down by major components, is shown in Table 3.

The system was demonstrated as scheduled in October 1972. According to the GAO report:

UMTA's administrator informed the Secretary of Transportation that this demonstration was an "unquestioned success." In our [GAO] opinion, this assessment is questionable. Three vehicles were used to give a demonstration to visiting dignitaries and members of the press at 75 percent operational speed and over half of the system. One of the three vehicles broke down on its first trip and was towed off the guideway; the other two vehicles completed a total of nine trips.
Table 3

PET SYSTEM COST EXPERIENCE\(^2\)

(millions of dollars)

<table>
<thead>
<tr>
<th></th>
<th>37.1</th>
<th>40.6</th>
<th>36.9</th>
<th>60.4</th>
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<td>COMMAND &amp;</td>
<td>6.6</td>
<td>8.3</td>
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<th>4/1/71</th>
<th>4/29/71</th>
<th>9/27/71</th>
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<th>1/1/73 actual IA costs</th>
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<td>JPL</td>
<td>Boeing</td>
<td>Boeing</td>
<td>Boeing</td>
<td>Boeing</td>
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<tr>
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<td>3</td>
<td>3</td>
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<tr>
<td>Guideway Miles</td>
<td>3.6</td>
<td>3.6</td>
<td>2.2</td>
<td>2.2</td>
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<tr>
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<td>10</td>
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<td>4-6</td>
<td>9</td>
<td>15</td>
<td>17</td>
<td>21</td>
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</tr>
</tbody>
</table>

\(^1\) Includes system engineering, project management and other miscellaneous costs.

\(^2\) Federal share excluding support costs.

\(^3\) Jet Propulsion Laboratory

SOURCE: Ref. 27, p. 17.
A system test/demonstration report was released in July 1973 which concluded that the Phase IA testing program satisfactorily demonstrated the PRT concept. However, the test results show deficiencies in almost every major subsystem. The test results identified certain subsystems as requiring redesign including steering, brakes, propulsion, vehicle control and communication, central computer, software, power collector, and guideway presence detectors. [27, p. 34]

Much of the cost escalation in 1971-72 was the consequence of the very tight October 1972 deadline for the initial prototype test and dedication. Only a year remained between actual construction started in October 1971 and the deadline. According to one report:

[Robert] Hemmes [formerly UMTA's associate administrator for R&D], who supervised the Morgantown project in its early stages says: "We tried to build the system before we had fully designed it. It's called 'concurrency planning,' which is taken from the A-bomb program and means that you design all the pieces and hope it will fit together later. So we designed the guideway, before we had the vehicles." Frederick R. Harris' Vice President, Frank E. LoPresti, confirms that UMTA's tight schedule had unfortunate results. "The schedule was dictated to us and we designed the guideway in an unheard of five months. We designed it before the criteria were known, and then the criteria kept constantly changing." [16, p. 51]

According to another account:

"There was a helluva lot of political pressure to make a show," recalls a Jet Propulsion official, who asks not to be named..."we didn't stop to do a proper systems analysis."

"The Alden design was sold as a pretty picture. Then we were never allowed to address ourselves to the project's competing requirements, which is what systems management is all about." [11, p. 21]

In addition, delays in completing Phase IA arose from numerous factors: The construction delay [of five months] was caused primarily by the excessive rainfall during the winter and spring months followed by Hurricane Agnes in June 1972; the delay in delivery of steel and construction materials; labor problems, including unavailability of
sufficient skilled tradesmen, especially electricians; difficult terrain and soil conditions; and uncharted underground utilities requiring special considerations.

By now, 3 1/2 years after ground was broken in October 1971, Phase I of the system is nearing completion. All 45 vehicles have been assembled and as of early April 1975, 18 were in Morgantown. A technical description of the system is contained in the Appendix. The system is undergoing final testing with almost all hardware in place. The major current problem is to achieve high levels of hardware reliability. This requires a continuing program of design improvements and other debugging as problems are identified.

All in all, the Morgantown case was a long and tortuous learning experience. The vehicle illustrated in Fig. 4 went through extensive redesign with the many malfunctions that cropped up as a consequence of prototype testing around the time of the October 1972 dedication. The guideway construction is itself within the state of the art, consisting of steel reinforced concrete, but problems arose in such areas as:

1. Designing the guideway before characteristics of the vehicle were well known—a consequence of the "concurrency planning" noted above. Lacking this knowledge, the construction engineers took the conservative approach and designed a guideway more massive and costly than that needed for the vehicle that was actually built.

2. Determining the best way of keeping the power rail ice-free, where there are two main alternatives: a) an electric heating system that, however, would have turned out to be prohibitively expensive because of a special surcharge the local public utility would have added to account for the fact that the system would add to peakload requirements during the winter; b) an anti-icing glyco spraying system using a small truck on the guideway, which is the system that was chosen.

3. Transmitting signals reliably in the communications cables which are laid in troughs in the guideway and covered over with epoxy. Because the concrete is porous, water can get
SOURCE: Ref. 8, p. 250.

Fig. 4—Morgantown Vehicle
to the cables, and wherever there are splices, nicks, or poor connections, problems both of signal leakage and of high resistance arise. Although this would seem to be a trivial problem, in fact a good deal of time has been spent in fault isolation, and in pulling portions of the cable out of the guideway in order to make repairs.

The most troublesome part of the system (as one would expect) is in command and control, where the vehicle on-board computers, the central computer system, and the software have to operate at extreme levels of reliability. With larger vehicles carrying more passengers than those envisaged originally, it has been possible to increase the length of headways to 15 seconds (in contrast to fractional-second PRTs discussed earlier), thereby placing less stringent requirements on the command-and-control system, and on design of the vehicle. Nevertheless, months of testing have been consumed in order to achieve an acceptable level of performance.

With the many modifications over the life of the project, the system has evolved into a far different concept from that of PRT described in Section I. In fact, the term PRT for Morgantown is a misnomer, for essentially it is a group rapid transit system, or GRT, by virtue of the fact that the vehicle carries up to 8 sitting passengers and 13 standees—a total of 21—in contrast to the very small PRT vehicles seating only several passengers. While the Alden-design vehicle weighed an estimated 3,500 pounds, the Boeing version runs to 8,700 pounds. It is 15 feet long, 6 1/2 feet wide, and operates with a 70 h.p. electric motor at a maximum speed of 30 miles an hour.

Because of the larger vehicle, and overdesign of the guideway even for that vehicle, the guideway is much more massive than those depicted in Figs. 1 and 2. In contrast, it takes on the dimensions of an elevated freeway ramp, too large to build along sidewalks and highways. The stations are also larger than those contemplated in PRT systems, where the stations are envisioned as essentially walk-up platforms from the sidewalk to off-line portions of the guideway.
In addition to the fact that this vehicle requires heavier guideways, it has three other notable features. It requires individuals to ride with strangers in automated vehicles; and question arises about the willingness of individuals to ride with strangers in driverless vehicles, especially late at night. Second, if a vehicle is disabled, it is not designed to be pushed by the one behind to the nearest off-line station. Rather, traffic must be stopped while a small truck is brought onto the guideway to push the vehicle to the nearest off-line station. This awkward strategy for moving disabled vehicles is used because 1) pushing one vehicle with another automated vehicle from behind could be tricky and pose safety problems to standing passengers; 2) the propulsion requirements for the pushing vehicle would have to be increased to move the disabled vehicle (unless its own propulsion is still operating) up the steep Morgantown guideway grades; 3) pushing requires an override of the mechanical and electronic anticollision devices—an override that entails one of the expenditures that were cut back when the system was facing large escalations in cost.

THE POSITION OF THE UNIVERSITY

Since the University will manage the system and be responsible for covering all of the operating and maintenance costs after acceptance from UMTA, it has understandably been concerned about the magnitude of these costs and the ability of the system to meet its needs. The University currently spends about $200,000 a year on conventional bus transportation described earlier. While the operating and maintenance costs for the PRT system will be higher, which is in part justified by the greater speed and greater capacity, obviously there is a limit beyond which the University would not want to go. In its first contract agreement with UMTA, the stipulation was made that operating and maintenance costs would be "reasonable and acceptable" but no dollar figure was specified. In 1974 the contract was written to stipulate the cost of $850,000 for the three-station system and $1.1 million for the expanded six-station system (if Phase II goes forward).
In addition to this cost burden, the University has expressed concern about the ability of the system to meet its needs. At the time contracting was underway for Phase IB, the Board of Regents informed UMTA that the three-station configuration was not a viable transportation system. Allegedly, it would not satisfy the transportation needs of West Virginia University nor the City of Morgantown, since it connected only three stations. Nor would it be economically viable, since buses would still be needed to service those areas not covered by the FRT. Moreover, the Board pointed out that expansion to six stations had been previously promised by UMTA, and the construction of the system in phases was agreed to by the Board for the convenience of the government.

Because the University was concerned at the beginning that it would not want to be saddled with a system that would be overly expensive or inadequate, it succeeded in having in the contract a clause that if the system did not meet certain specifications, the University reserved the right to refuse to accept the system, and to require UMTA to dismantle the system and restore the land to its original condition—an effort that would cost $7 to $10 million.

In May 1975 UMTA and the University reached agreement on plans for Phase II funding of the system. The agreement stipulates that UMTA will provide another $4.3 million dollars for a year-long start-up and operating program (starting in mid-1975) and for architectural and engineering design for expansion to five stations. Furthermore, UMTA has agreed to advise the House Appropriations Subcommittee of its intent to fund expansion of the system to the five-station configuration if the cost of expansion does not exceed $53.8 million in 1974 dollars and if the system works satisfactorily by the end of this additional development period. In turn, the University has agreed to delete the requirement for the sixth station and has agreed to assume ownership of the system provided that it works satisfactorily during the first year of operation.

The system started carrying passengers in the fall of 1975. Because this first year is one of continuing development, students are being carried free of charge, while tickets are sold to the general public for
twenty-five cents apiece. For the 1975-76 school year the Board of Regents is contemplating a student charge of $25 per semester. Typical of development projects, a number of technical problems have arisen (sticking doors, malfunctioning turnstiles and such).* These difficulties are being worked out and the overall level of reliability is rising.

III. APPLICATION OF OUR CONCEPTUAL FRAMEWORK

For our purposes, a central question relates to the extent to which the project is generating useful information, judged by how it reduces uncertainty in each of the five dimensions included in our conceptual framework: Technology, Cost, Demand, Institutional Considerations, and Externalities. Notably, the stated objectives of the project fit well into our five dimensions shown in brackets. These objectives as defined by UMTA [27, pp. 51, 52] in June 1973 were to:

1. Install in an urban area a full-scale, operational PRT system which could be studied, evaluated, and emulated by other communities; [all five]

2. Develop a system for personal mobility that would provide an effective transportation alternative to the University bus and personal automobile; [technology, demand]

3. Demonstrate the operational feasibility of the PRT system and gain a measure of its public acceptance; [demand, cost]

4. Qualify the PRT system concept for an UMTA capital grant program and to obtain data and documentation for duplication of PRT systems in other geographical locations; [all five]

5. Demonstrate the impact of the PRT system on the Morgantown community—appearance, economics, transportation; [cost, demand, externalities]

6. Verify capital and operational costs and accumulate information on the safety, reliability, and maintenance of a PRT system. [technology, cost]

Each of these dimensions will be discussed briefly in turn, along with reasons why the Morgantown demonstration is or is not substantially reducing uncertainty in each of the dimensions, and thereby achieves, or falls short of, these objectives.
TECHNOLOGY

At the beginning of the Morgantown project technological uncertainty was high. Never had such an automated guideway system been installed with off-line stations in an urban environment. The only similar systems were those developed for airports, including Seattle-Tacoma, Tampa, and Dallas-Ft. Worth that use little or no switching. Design and development of a vehicle with steering on all four wheels, an on-board switching system in the vehicle (rather than switching on the guideway), the on-board computer and, especially, the computer software posed substantial challenges. Guideway construction itself is within current state of the art, but uncertainties about maintaining ice-free the guideway power rail has proved a problem. (De-icing of the guideway surface itself, consisting of circulating hot water in pipes embedded in the concrete, had a straightforward solution.)

In general, it is fair to conclude the Morgantown demonstration is successful in reducing technological uncertainty for GRT but not for PRT. That is, for group rapid transit involving relatively large vehicles with headways of 10, 15, or 20 seconds, and using conventional electric propulsion, braking, and rubber tires on concrete, the demonstration will provide useful information about the day-in, day-out operating characteristics and problems of the vehicles, the problems involved in keeping the guideway and rail free of ice, and the use of computers and associated software for command and control in the relatively small 3- to 6-station system. The computer software will be transferable to other sites, though it would need to be elaborated in a larger multistation network. Data on mean time to failure of the vehicles and the effect of vehicle failure on system reliability will prove useful elsewhere. The difficulties encountered with disabled vehicles, involving shutting down the system and using a conventional small truck to push the vehicle to the nearest station, can be evaluated against the alternative (at least on paper) of having individual vehicles designed for a pushing capability. Problems encountered in the construction of the system, including those of coping with uncharted underground utilities, and requirements for specialized labor in construction, is also useful experience for those contemplating similar
systems elsewhere. The problems of cable malfunction and fault location discussed above will also be important elements entering cost estimates and scheduling of construction in subsequent systems.

So far as PRT is concerned, the Morgantown experience is much less relevant. Use of fractional-second headways with small vehicles, development of linear induction motors for traction and braking, and uncertainties about construction of small, low-cost guideways are not addressed in the Morgantown system. More relevant in reduction in uncertainty is the experiments with PRT systems being conducted in other countries, most notably Japan, France, and Germany. [9, p. 23-25]

COSTS

Coping with technological problems in GRT, Morgantown also reduces uncertainty with respect to cost of replicating the system elsewhere. One can visualize the use of the Boeing vehicle essentially as it has now been developed for use in similar systems. With transferability of computer software and guideway design, cost estimates can be made more accurately than those of four years ago. However, even for GRT some cost uncertainty remains. According to the GAO staff study, expansion of the system to four stations would involve an additional cost of about $21 million, expansion to five stations $48.5 million, and to six stations (the full Phase II) $53.8 million [27, pp. 55-56]. Yet even with all the experience accumulated to date, these figures are not without challenge. In its comments on the GAO report, DOT says with respect to the five-station alternative:

The cost estimate of $48.5 million is based on an extrapolation of the Phase IA and Phase IB cost history. From this data, it is difficult to determine which costs are nonrecurring R&D and which are recurring. If the design of the Phase II were complete, the cost to expand the system could be achieved more economically. The estimate would then be based on the actual design of the system, rather than an extrapolation of past efforts heavily weighted with R&D effort. [27, p. 83]

The implication of this view is that because of the difficulty of separating nonrecurring R&D cost from the other costs of completing the
three-station system, the information on costs from Phases IA and IB is of limited value in estimating the cost of expanding even the Morgantown system to encompass additional stations, let alone the problem of estimating costs of replicating the system elsewhere.

For reasons similar to those discussed above with respect to technological uncertainty, uncertainty of cost estimates of developing and operating small vehicles with fractional-second headways on automated guideways above existing sidewalks and streets will be little affected by what is being learned in Morgantown.

DEMAND BY THE PUBLIC

The Morgantown demonstration will do little to reduce uncertainty with respect to demand for either PRT or GRT. Because the system has only three stations the flexibility of such a system can hardly be demonstrated. At best the rider can choose to bypass only a single station. Even were the system expanded to six stations as part of the completion of Phase II, the number of choices would be far more limited than those envisaged in a system covering a central business district.

Moreover, the fact that Morgantown does have a built-in ridership—one of the features mentioned above that led to Morgantown as a selection for the demonstration—limits the value of the demonstration in examining various dimensions of demand. Since the bulk of the riders are students, a relevantly homogeneous group, we will have less useful data about the willingness of individuals to ride in automated vehicles with strangers than would be the case with the more heterogeneous population characteristic of major metropolitan areas. To be sure, townspeople will also patronize the system, but one estimate by a knowledgeable individual is that even in the six-station system, about 75 percent of the riders are expected to be University students.

Moreover, payments for bus service today are part of the student's tuition. Unless the University requires the student to pay directly, we will not have a good idea of how much the student values the new service. More specifically, if all or a significant portion of the fare for GRT
service is absorbed by a flat semester fee, then even a large shift of student ridership to GRT and away from personal automobiles would tell us little about the demand for GRT—or PRT—service in a typical metropolitan setting, where the willingness of riders to pay on a per trip basis is of central importance.

Other elements may be learned relating to public acceptability: the ease or difficulty with which people have in following instructions in ordering cars on demand and selecting destination stations; the appeal that the vehicles have in terms of comfort, speed and reliability; the extent to which vandalism of automated vehicles turns out to be a problem; the nature and frequency of accidents; and the extent to which individuals are willing to take PRT even if it requires a drive or a long walk to and from the PRT station. In virtually all these cases, however, we must note that data generated would likely be more useful if the users of the system were a better cross-section of potential riders instead of being predominantly University students. Their common origins and destinations and alternatives, including driving on extraordinarily congested streets, will render their responses as not good measures of what could reasonably be expected elsewhere.

INSTITUTIONAL FACTORS

Here one is primarily concerned about changes in organizational and operating procedures for the adopting agency, potential labor union problems, and other considerations bearing upon modifications in behavior of the adopting agency required to successfully integrate the innovation. Again the Morgantown demonstration is likely not to prove very useful. Since the system is not being operated by an ordinary transit authority, but rather by the regents of West Virginia University, the problems faced by a transit authority in satisfactorily integrating PRT or GRT cannot be explored to a significant extent. For example, we would expect a transit agency adopting PRT to face problems of phasing out buses on some routes, perhaps facing labor union problems in reducing its labor force as a consequence of automation, while at
the same time trying to satisfactorily integrate PRT into the schedules and routes of its remaining bus or other conventional transportation links. But the existing city-owned public transportation system in Morgantown will continue operating apart from the University system. Thus, we cannot expect to learn anything significantly about problems of integrating conventional transport and PRT. Nor will we learn much about labor union problems since a few if any workers are likely to be displaced directly as a consequence of the use of the new system. On the contrary, the 43 employees estimated as the steady-state requirement for the three-station system is greater than the number of employees that operate the buses for University students today. If anything, then, employment is likely to rise rather than to fall as a consequence of putting the system into service.

EXTERNALITIES

Here we are concerned with the extent to which PRT reduces traffic congestion, air pollution, lower noise levels, either adds to or subtracts from aesthetics. The Morgantown demonstration will provide useful information on the level of noise of the system in the day-in, day-out operation with varying levels of traffic demand. It will also provide information on reduction of traffic congestion and air pollution to the extent that individuals do move out of their automobiles.

On the aesthetic side, Morgantown will give the viewer an impression of how CRT would appear, with its relatively large guideway and stations, in other settings. However, it does not provide good information on the problems and other considerations bearing on the appearance of a PRT system with its smaller cars, lighter and less costly guideway, and small sidewalk stations. Some argue that the Morgantown system has a negative aesthetic value because of its large guideways and stations. Potential adopters can visualize the amount of tree-cutting, demolition of buildings, and difficulties of obtaining adequate right of way to install the same kind of system in their own city. On the other hand, advocates of PRT point out that even the Morgantown
guideway is over-designed for the size of cars being operated, and
that a genuine PRT system with small prefabricated guideways running
along the sidewalks, as shown in Fig. 1 above, would not detract from
the appearance of the downtown area. Regardless of which view one
takes, the information generated by the Morgantown demonstration will
not settle the debate.
IV. LESSONS FROM MORGANTOWN

QUESTIONS OF SITE SELECTION

From the above it is clear that the difficulty in reducing uncertainties, especially with respect to demand, institutional and environmental factors, is a result of Morgantown's being a poor site for a PRT (or more accurately a GRT) demonstration. As several knowledgeable individuals have told the author, the Morgantown effort has ended up being much more of a development than a demonstration activity. To obtain useful data on the demand for GRT or PRT service, and in particular, a better idea of how it affects modal split, requires that the system be large enough in terms of number of stations and line miles to provide potential riders with a wide range of choices. If flexibility is one of the most important characteristics to be offered by automated guideway systems, then a large degree of flexibility must be built into a demonstration project. This cannot be done with either a three-station or a six-station system confined largely to university users.

Expressed differently, some of the very reasons why Morgantown was picked as a site—the captive ridership of university students, the five-peak period day coinciding with class changes, and the particularly severe problems of traffic congestion in the narrow Monongahela Valley—are the very characteristics that make it unsuitable as a site for a demonstration project with applicability elsewhere.

Likewise, on the institutional side, one would have preferred a demonstration in a major metropolitan area that would have required integration of the PRT or GRT into an existing surface transportation system in order to test problems of coordinating schedules, dealing with labor union problems, and providing a better notion of public acceptance where riders must switch from one mode to another.

On the environmental side the Morgantown guideway is relatively short (in comparison to the hundreds of miles of guideway envisioned by PRT advocates to provide wide area distribution in large cities), and it roughly parallels the Monongahela River along land that is usable for little else. More useful in assessing visual impact would be a
demonstration system threading along existing city streets with multi-
story buildings on each side and also along tree-lined streets in resi-
dential areas.

So far as we have been able to determine in this study, there was
no careful comparison of alternative sites by UMTA for a PRT demonstra-
tion project. The University wanted the system built, UMTA was under
pressure to fund it, and the easiest way to do it at the time was to
regard it a demonstration project, which could come out of UMTA's R&D
fund rather than being financed, as transit systems frequently are,
through the capital grant program where normally the local agency must
contribute 20 percent of the total cost.

Perhaps our later work will corroborate the evidence here that site
selection is very important if the demonstration is to reduce uncertainty,
particularly in the four dimensions of cost, demand, institutional con-
siderations and externalities.* If we determine that site selection is
indeed a critical variable cutting across our case studies, we will want
to concentrate on the detailed considerations that government agencies
should bear in mind, including design competitions and a carefully
phased selection process, in deciding which of several sites is most
appropriate for the demonstration at hand. A major problem, of course,
is that site selection can get so easily involved in the political
process. We anticipated when we began our case studies that politics
would enter heavily. One of the obvious places where it does so is in
site selection--an unfortunate circumstance insofar as an inappropriate
selection can seriously compromise the project as a demonstration activity,
in contrast to an ordinary capital grant activity where the project is
built explicitly to serve the particular needs of the community.

* Analogously, for demonstration projects that are not site specific,
for example, the nuclear freighter Savannah, the basic consideration is
a design addressed to the real needs for which the innovation is likely
to be appropriate. In the case of the Savannah, a large containerized
freighter version was needed, rather than the passenger/freighter version
that was grossly inappropriate to test the potential demand for high
speed, long distance freight shipment for which marine nuclear propulsion
seems best suited.
COST/PERFORMANCE/TIME SCHEDULE TRADEOFFS

As in other activities, tradeoffs exist among cost, performance, and time schedule. Generally speaking, the shorter the time permitted for the activity, the higher the cost and/or the lower the performance (judged in terms of the ability of the project to reduce the uncertainties addressed above). Or the lower the cost, the lower the performance and/or the greater the required time. The Morgantown project was badly hampered by the requirement to have a prototype test and inauguration in October 1972 to phase properly with the November presidential election. Because the guideway had to be designed and built without good knowledge of what the vehicle characteristics would be, the engineers took a conservative approach and overdesigned at a substantial additional expense. As shown in Fig. 3, the construction cost, including guideway, estimated on 2/11/72 by Boeing at $20.3 million was nearly double the $12.3 million estimate by JPL for the same length guideway on 4/29/71. This increase was partly a result of overdesign and the extra costs involved, including overtime, to rush the guideway to completion. Likewise, Boeing undertook a crash effort to have vehicles designed, built, and tested at the factory before delivery to Morgantown.

The high technical uncertainty existing at the beginning of the program, combined with the stringent time schedule, contributed to the project’s failure to reduce uncertainties in the demand, cost, institutional, and externalities dimensions. It was because of the escalating costs early in the program that the decision was made to cut back from six to three stations for Phase I. The three-station system, having less scheduling flexibility than the six-station, will not demonstrate as well the response of public demand to PRT or GRT (although as discussed above, even the six-station system would have nowhere near the flexibility of those envisioned in a normal metropolitan setting).

On the cost side, the expenditures incurred in meeting the October 1972 deadline are partly responsible for the continuing level of cost uncertainty for PRT and GRT. So many factors extraneous to replication of the system elsewhere have intruded that it is all the more difficult to estimate future costs on the basis of the Morgantown experience.
STRATEGIES FOR REDUCING TECHNOLOGICAL UNCERTAINTY

Perhaps the most serious difficulty in the Morgantown case was the attempt to integrate an advanced technology into an operational setting which requires careful coordination among governmental agencies at local, state, and federal levels as well as with numerous groups in the public and private sector. With cost escalations that one can expect in developing a new technology (especially when one begins a program based on such poor estimates as those made in mid-1970) the reactions of potential adopters elsewhere are likely to be adverse. That is, even though a technology may indeed be promising in solving a wide range of needs, a demonstration project that exhibits cost escalations, congressional pressures, both positive and negative, schedule slippages, and adverse reports in the press is likely to have a negative impact. Although the effect is impossible to quantify, we have been told by several that the Morgantown project may retard development of PRT because of a loss of credibility that UMTA has suffered in the eyes of Congress. Similarly, the GAO "is concerned that the problems and criticisms of the Morgantown project's management and cost will jeopardize further research and development of PRTs by federal and private interests." [27, p. 5]

Thus, even apart from the intrinsic merits of a particular demonstration project, the contrasts between performance and earlier estimates and promises, and the reactions of Congress and other groups during the course of the project, can have a significant impact on prospects for diffusion.

For this reason among others, some have suggested that most of what has been learned in Morgantown in terms of reducing technological uncertainty could more cheaply and easily have been learned on a test track. For example, the GAO study concluded that:

Building such a system while coping with the intricacies of a downtown environment make it a very expensive learning process. We believe that the feasibility of new transportation technology should be tested away from the central business district, e.g., a test track, before installing the operational system. We suggest that this policy be applied to all UMTA research and development projects. [27, p. 48]
Thus, a guideway could have been constructed in an isolated spot to permit vehicles to operate up to full speed; several off-line dummy stations with attendant switching capability could have been constructed; software could have been developed both using simulation techniques and within the context of the test track operation; and a small fleet of vehicles could have been designed and built as part of the overall system test. Several advantages accrue from the test bed approach:

1. Whatever mistakes are made and technological fixes are required can be accomplished in private without media coverage and a panoply of pressures associated with the visibility of a project in the middle of the city.

2. The test bed can be protected against children, vandalism, etc., at times when it is especially vulnerable as a consequence of such items as ladders and other equipment lying around that are required to construct and maintain it. A remote test track can easily be fenced.

3. With a test track one can build long enough runs and design it with other characteristics to really test what one wants to test. If, for example, one wants to test the software problems in command and control going to a large number of stations, the test track can include 10 or 15 shortly spaced dummy stations along the way without the constraints that are faced in an operational setting, or without facing the costs of actually constructing stations, as in the Morgantown case. Steep inclines can be built into the track to test the suitability of the technology in coping with them without necessarily going to a hilly part of the country. If one wants to test for problems of snow and ice removal, then it is easy enough to place the track in the northern portion of the country, subject to the full extremes that one would anticipate in operational service. In short, while one cannot test some aspects in a test bed operation, especially the reaction of the public and the level of public demand for the service, one does have far greater flexibility than in an operational
setting in testing a wide variety of combinations relevant to the development of the technology, and in doing so, substantially reduce uncertainty in that dimension.

4. If the test track is built in an operational setting and is shown to be indeed applicable to the city's problems, strong and premature pressure may build up to use it before it is fully debugged, and this may cause a subsequent adverse negative reaction both in the city of operation and in the eyes of potential adopters elsewhere. Under the best of circumstances some technological debugging will be required after the system is placed in operation (recall the problems with the Boeing 707 in the early months of its airline use).

As an implication of the above, the Morgantown experience suggests that one should develop technology first, then address in a demonstration project the other dimensions of uncertainty—demand, cost, externalities, and institutional considerations. Expressed differently, what a test track does best is to permit one to experiment with a technology to iron out the bugs and to develop it to a stage where cost estimates can be made for a specific operational setting with a tolerably high level of certainty. A demonstration program, on the other hand, is especially suitable in testing the technology in the other dimensions. For example, if one wants to learn about the effect of the system on modal split, public appeal, problems of vandalism, and the willingness of people to ride in automated vehicles with strangers, then the way to proceed, indeed, probably the only way, is to have a project operating in a real life environment. No amount of paper study or test track experience can pin down these kinds of uncertainties.

Likewise on the institutional side, problems of labor union agreements and adopter change requirements can be examined best with a system working in a representative urban environment.

With respect to externalities, problems of noise in day-in, day-out operation, and the reaction of the public to it, and questions of aesthetics can again be judged best in a real-life operating environment.
With respect to cost, the test bed is valuable in reducing technological uncertainty which is one important input on the cost side. But other cost elements also enter in, especially operating and maintenance, which can be determined only with experience in a real-life setting. So again a demonstration project following a test track experimentation program can be useful (recall again that at the time the Boeing 707 was placed in service, the airlines were pleasantly surprised that maintenance costs were lower than had been earlier estimated, partly because the jet engine turned out to be more dependable in day-in, day-out service than had been predicted).

Of course, each urban environment will have its own characteristics that will make full generalizability impossible. Still, a demonstration operating in a suitable site will provide potential adopting agencies elsewhere with a better notion of the kinds of problems that they may encounter than would be the case with only test bed experience or with an operating site with numerous unique characteristics.

THE ROLE OF COST SHARING

One characteristic we must bear in mind in our case studies is the extent to which cost sharing between federal and local agencies has a bearing on outcomes. In principle, sharing of costs by local participants would seem important because it may provide a reflection of their interests and genuine willingness to make the project successful in terms both of satisfying local needs and of providing information valuable to outside potential adopters.

For example, if the local agency is required to put up a substantial portion of total funding, it may be able to exert counter-pressure along with other groups against political forces that result in imposition of unrealistic time schedules on the project. With its own money at stake, the local agency may be under more pressure to cooperate with federal agencies in making the project work well; without cost sharing, it may impose extreme demands on the federal agency, since it may feel that it has little at stake.

There is one contrary consideration to note, however: the willingness of local agencies at a particular site to contribute may or may not
have much to do with the representativeness of that site as a demonstration whose results will be widely applicable elsewhere. Thus a conflict can arise between the desirability of local cost sharing and appropriate site selection along lines discussed above.

With respect to the effect of local cost sharing, the Morgantown experience is unclear. For Phase I, local cost sharing took the form of land required for rights of way that has a total estimated value of $2 to $3 million. Some of this included outright purchases, including $270,000 spent by the County and $400,000 to $500,000 spent by the University. For Phase II the University applied for a capital grant in 1964, where it is proposing to donate $13.7 million of needed right of way as its 20% matching share (for a total estimated cost of almost $69 million), as required in the capital grants program. However, controversy has arisen about the true value of this land. According to one report:

An UMTA official familiar with the project raises doubts about the University's figures. "In order to get around the fact that the University has no cash," he says, "it is possible that the land may have been assessed at 20 times over value, and the estimate of the entire project cost-inflated by 125%... In reply W. V. U.'s Harlow [president of the University] says: "It is very high priced real estate. The estimates we got were done by professionals—it wasn't something we just whopped up." [16, p. 52]

Although demonstration projects, coming out of research and development monies typically do not require a specific percentage of local cost sharing, federal agencies might be well advised in the future to require some cost sharing to reflect the fact that aside from the value of the project as a demonstration for use elsewhere, it has a direct value to the community in which it is being built. Moreover, this contribution by local agencies might include hard cash in addition to items whose value can be determined only by assessment. This possibility can be set forth only tentatively at this point, since we don't have strong evidence one way or another. But it could well provide the basis for one of our hypotheses to be tested in our subsequent work.
A CONCLUDING NOTE

It is well to end with a portion of the congressional testimony of William F. Hamilton of the General Research Corporation, who summarizes much of the problem of Morgantown, and of PRT.

We have all heard of the Morgantown PRT demonstration. Demonstration it is, but PRT it is not, because the two are presently incompatible. The fundamental problem in PRT is safe, reliable automation of many small, closely-spaced cars. But if there is any substantial safety problem in a system, to demonstrate it with real passengers in daily service would be clearly irresponsible. However well-intentioned, the Morgantown demonstration had above all to be safe, and as its specifications were written, it became a PRT in name only. Morgantown's cars must maintain spacings 20 times those of PRT, as it is usually defined. It follows that each car must carry 20 travelers at once; then intermediate stops and transfers are unavoidable, and service is scarcely more personal than that of a conventional bus.

Thus the potential of PRT still remains to be explored. Unless national transportation policy is transformed, it will be approached slowly at best, while transit funds pour year after year into bus and rail systems which are virtually certain to do little for either the transit traveler or for the overall quality of urban life. It is undeniably simplest, easiest, quickest, and safest to support conventional transit. But if transit which attracts high patronage is the ultimate goal, our only real hope lies along the difficult path to PRT, a path where uncertainties abound, where risks must be squarely faced, and where the great payoff may be far beyond the next election. [26, p. 164]
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APPENDIX

DEPARTMENT OF TRANSPORTATION

URBAN MASS TRANSPORTATION ADMINISTRATION

TECHNICAL DESCRIPTION

MORGANTOWN, W. VA., PERSONAL RAPID TRANSIT SYSTEM

July 10, 1974
GENERAL

The Morgantown Personal Rapid Transit (PRT) system consists of small, automatically-controlled vehicles which operate on a dedicated guideway either in a scheduled mode or in a passenger-demand mode. The rubber-tired, electric-powered vehicles will each carry up to 21 people. (8 seated, 13 standees)

The system connects two of the West Virginia University campuses and the central business district (CBD) of Morgantown, covering a distance of over 2 1/4 miles. The guideway itself totals 27,000 feet, including travel in both directions as well as those sections devoted to the maintenance area, off-and-on ramps and loops. In the year-long prototype test phase of this installation, 5 vehicles were operated over this network connecting 3 stations and a limited maintenance facility which also houses the Central Control Center.

The system can operate in either a demand or scheduled mode, depending on the anticipated number of passengers expected to use the system. In either mode, a passenger entering a station will first insert a fare card into the fare collection entry-gate which triggers the destination selection panel. The passenger now is able to select, by depressing a button, the destination station of his choice. In demand mode operation, a car may be immediately available upon a passenger's request; however, the waiting time for a passenger between selection of his destination and the availability of a vehicle (for his trip) will never exceed two minutes. In scheduled mode, vehicles are routed throughout the entire network on a scheduled basis commensurate with the prognosticated passenger demand. In this mode, passenger waiting time will not exceed five minutes. All
passenger trips in either mode are non-stop from origin to destination. The system operates with a 15 second headway (interval between vehicles); overall control of the unattended vehicles is maintained from the Central Control Center by use of redundant computers which communicate with the vehicles through inductive loops buried in the guideway.

The Morgantown PRT system has three major elements: Structures and Power; Vehicle, and Control and Communications.

STRUCTURES AND POWER

This system includes the guideway structure, the electrical power substations, the station facilities, the central control facilities, the guideway heating system and the maintenance facility. The main guideway is a double-lane guideway with two-way travel. The stations are constructed with multiple channels, each channel having four vehicle stopping positions (berths). These channels are single-lane guideway construction, permitting one-way travel only. Stations are located off-line from the main guideway to assure vehicle movement on a non-interference basis. The system power is 60 Hertz, 23,000 volts provided to a main substation which transforms and distributes three phase, 575 volts to the guideway power rail. The maintenance area includes a vehicle storage section with 10 storage positions, a test track, a vehicle and equipment service building and the Central Control Center.

VEHICLE

The Morgantown PRT vehicles, small by mass transit standards, carry up to 21 passengers -- 8 seated and 13 standing. The vehicle size was selected to provide economical service during both peak and
low periods. The vehicle is 15.5 feet long, 6 feet wide, and weighs approximately 8,700 pounds empty. Maximum vehicle speed is 44 ft/sec, (30 miles per hour) which is provided by a 70 horsepower DC electric motor. Rubber tires and an air bag suspension system provide a quiet, comfortable ride. The vehicle responds to remote controls and commands from the Central Control Center operating fully automatic. Acceleration is nominally .0625 g with maximum jerk of 0.125g/sec. Steering guide wheels follow guide-rails mounted on the inner side of the guideway. Either left or right steering can be used, depending on the desired route. Power is collected from a rail mounted above and parallel to the steering rail. Three phase, 575 volt power is received, rectified and controlled on board the vehicle for operation of the DC motor. Electric power also operates the vehicle lights, air conditioner, pneumatic and hydraulic pumps and the control system.

CONTROL AND COMMUNICATIONS SYSTEM (C&CS)

The C&CS is divided into three major elements: the Central Control and Communications Subsystem (CCCS); the Station/Guideway Control and Communications Subsystem (S/GCCS), and the Vehicle Control and Communications Subsystem (VCCS). The maintenance facility houses the CCCS. Operating stations are the Engineering, Beechurst and Walnut Street stations. The CCCS computer supervises transit system operations. Dual redundant computers in the stations and the maintenance facility control vehicle and transit operations within local control zones on the main guideway, local station guideways and the maintenance guideway. A special purpose processor (the VCCS) on board the vehicle controls
vehicle movements and operations from commands generated by the station computers. The link between the vehicle and the CACS is an inductive communication network which transmits vital signals by tones and nonvital signals by digital transmission.

Dual redundant central computers provide automatic control of the movements of the vehicles either through a predetermined stored program destination schedule or on a passenger-activated demand basis. The system operator, located at the central control point, monitors the system and exercises direct control during system start-up and shutdown and in case of system failure. At all other times, the central computers provide control and supervision of vehicles in the stations, maintenance area and on the guideway.

The operator can call on certain software routines by typing the required call-up message on a CRT keyboard. The software routines allow the operator to restart the system, run vehicles at a reduced performance level, assign vehicles to various locations, and perform other system control or override actions. Performance level modification involves running vehicles at speeds lower than normal and can be used during poor weather conditions, guideway maintenance operations, or under other conditions. Performance level modifiers available to the operator are 0%, 50%, 75% and 100%.

A synchronous speed tone generator drives inductive guideway loops and provides speed commands of 44fps, 33fps, 22fps, 8fps, 6fps and 4fps to the vehicle. The primary speed control and separation control system is the point follower or synchronous control system. In concept,
the point follower system consists of moving slots circulating around the main guideway and controlled by the central and station computers. The slots are established, a vehicle is dispatched into an open slot by the station computer at the direction of the central computer and the vehicle maintains position in the slot during its trip. An on board speed and position controller maintains the vehicle velocity as required to travel specific distances in a set time interval.

Periodic calibration loops provide a reference to the on board controller for self-calibration and removal of bias or random error. Slot allocation is performed by the central computer and slot monitoring is performed by the station computers. Slot monitoring includes comparing the time a vehicle arrives at vehicle presence detectors located at intervals along the guideway to the expected time of arrival as determined by the station computer.

**SYSTEM OPERATION/CONTROL**

The central console equipment permits an operator to monitor and control the transit system. The console includes operator display and control equipment. An alphanumeric CRT terminal provides detailed status reports and permits operator/computer communications. Abnormal status conditions in vehicles, the power distribution system, and other system support functions are displayed by a multiple-point annunciator panel and an audible alarm.

The station computer controls vehicle switching, stopping, door operations in the station, stations dynamic displays and response to inputs from the destination selection units. The computer in the maintenance facility duplicates station computer operations and controls the test track and maintenance queue slots.
Steering commands are given by the station computer to guide the vehicle through specified routes on the guideway and in the stations. Steering (switching) commands are generated by the station switch tone transmitter. Verification is received by the station when steering commands are responded to by the vehicle. If this verification is not received, the vehicle will be stopped automatically.

The station stop tone transmitter generates a reference signal to drive the vehicle to a precision stop plus-or-minus 6 inches in the station channel berth. The loop is a figure eight pattern, with the vehicle decelerating from 4 to 2 fps after entering the loop and decelerating to a stop after passing the center point of the loop crossover. The station computer commands vehicle doors to open and close for passenger loading and unloading.

Equipment installed on the guideway includes digital data cables, tone signal cables, presence detectors, cables and cable trays and installation hardware. All active electronics which drive the cables are located in the station or maintenance C&CS rooms. The nonvital frequency shift keyed (FSK) command data are inductively coupled to the vehicle from the guideway-mounted inductive loop cables. The FSK link can address and interrogate a specific vehicle or all vehicles in the network. The FSK signals are driven over the same inductive cables that command the vehicle speed and transmit performance level modifiers to the vehicle. The calibration tone transmitter and loop transmit a tone signal to the vehicle antenna to provide measured distance references. This nonvital tone is used by the VCCS as a reference in calibrating the vehicle odometers. This process removes
error accumulated since the last loop was passed.

The guideway Control and Communications Subsystem incorporates the Collision Avoidance System (CAS) which is independent of the primary control systems of the SCCS and CCCS. The dual CAS consists of independent hardware and software elements, each of which ensures that vehicles are spaced at safe stopping distances. The fail-safe CAS unit is responsible for overriding controlled vehicle movement along the entire guideway network to prevent collisions. The guideway is segmented into blocks. Presence detectors sense vehicle presence within each block and are used to set hardware and software logic which controls the transmission of a safe-to-proceed tone to individual blocks. As a vehicle enters a block, the block immediately behind the vehicle is turned off (safe tone removed). Loss of the safe tone signal results in emergency braking of a vehicle. The CAS is designed for operation throughout the guideway, in the station ramps and in the maintenance guideway area.

The VCCS responds to guideway/vehicle inductive communication loops to regulate vehicle speeds and generate commands to the vehicle. The inductive receiving antenna on the vehicle picks up vital modulated tone signals from the guideway control and communications loops as well as nonvital FSK messages. The VCCS communication unit, which receives the information, includes the fail-safe collision avoidance safe tone receiver and the switching command transceiver. The FSK transceiver is bi-directional and feeds the transmit antenna, linking asynchronous vehicle performance data to the S/GCCS. The fail-safe command-speed receiver processes the speed tones to the command speed decoder, which
inputs the command speed to the speed and position controller and
the overspeed detector.

In the event of a speed change command, the VCCS profile
controller modifies the speed command at a constant rate prior to
processing by these units. The redundant, fail-safe overspeed detector
energizes the emergency brake control if the vehicle speed exceeds
commanded speed by 3fps.

The fail-safe Collision Avoidance Receiver detects the vital safe
tone signal and the absence of a safe tone signal results in emergency
braking. Presence of the safe tone commands "go at commanded speed".
The switching command transceiver generates the vital signals to the
vehicle switching control system. Once switching is accomplished,
this unit sends a verification signal to the wayside switch tone unit;
in the absence of such verification the emergency brake is applied
automatically.

The VCCS control unit includes the velocity and position error
processor, the profile controller, and the stopping profile logic.
These functions are performed on board the vehicle and control speed
and position relative to nominal profiles in constant speed regions,
transition zones and at station stopping positions.

The VCCS data handling unit processes vehicle door control signals;
signals associated with vehicle performance monitoring and C&CS status
monitoring, and identifies the vehicle on the guideway to enable proper
identification of data received by the stations and the central control
computers.
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HYDRAULIC KNEE PROSTHETIC DEVICE

by

Richard A. Rettig
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LIST OF ABBREVIATIONS USED IN THIS CASE STUDY

A/K  above-knee
B/K  below-knee

NAS-NRC CPRD  National Academy of Sciences-National Research Council Committee on Prosthetics Research and Development

NCHS  National Center for Health Statistics
NYU-PDS  New York University-Prosthetic Devices Study
S-N-S  Henschke-Mauch Swing-N-Stance System
TDS  technology delivery system
UCLA  University of California at Los Angeles
VA  Veterans Administration
VAH  Veterans Administration Hospital
VAOPC  Veterans Administration Outpatient Clinic
VARO  Veterans Administration Regional Office
I. THE HYDRAULIC KNEE

Prosthetic devices—artificial substitutes for missing body parts—are generally categorized as artificial limbs or sensory aids. Artificial limbs, in turn, are categorized as upper and lower limb, respectively, and then, more precisely, by type of amputation.

In this case study, we are concerned with the above-knee (A/K) amputee population and with a family of recently developed fluid-control prostheses for this population. Above-knee amputees are those individuals whose amputation lies between a complete hip disarticulation and a complete knee disarticulation and who are differentiated according to length of thigh stump.

Limb loss is an ancient problem of man and prosthetics consequently has a long history. The first artificial leg known to employ articulated joints for A/K amputees, for instance, was developed by Ambroise Paré, a French army surgeon, in the middle of the sixteenth century. A wooden, articulated prosthesis was first used in London in 1800 and introduced with modifications into the United States in 1839. The Civil War generated interest in artificial limbs, partly because of the large number of amputees and also because of the payment by Federal and state governments for limbs for veterans. Neither the limited U.S. involvement in World War I, nor the inter-war period, stimulated much interest in prosthetics in this country. Thomas and Hadden reemphasized the view in the inter-war period, however, that fit and alignment of prostheses were the most critical.

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1 Fluid-controlled artificial knee prostheses include both hydraulic and pneumatic devices, though the former are by far the more technologically complex. This case study deals only with hydraulic mechanisms which we will refer to as hydraulic knees.

2 A stump is considered long, for instance, if more than 50 percent of the femur remains, medium if the remaining portion is 30 to 50 percent, and short if the femur is less than 30 percent of the original length. Veterans Administration, Department of Medicine and Surgery, Prosthetic and Sensory Aids Service, Program Guide: Selection and Application of Knee Mechanisms, G-7, M-2, Part IX, August 1, 1972, p. 15.

factors in limb success and they also emphasized the importance to successful results of cooperation between surgeons and prosthetists.

Conventional prostheses for A/K amputees are essentially mechanical friction devices fabricated from wood and leather or laminated plastics. These prostheses constitute a simple "single-axis free-swing pendulum." One type has a free knee swing where only the mechanical resistance between the moving parts affects the pendulum action. A larger number of devices, though, have an adjustment mechanism which speeds up or limits portions of the swing. Extension aids, for instance, increase the tendency of the leg to extend, while resistance mechanisms limit the swing during both flexion and extension phases of walking. Accordingly, "in a properly aligned mechanical friction limb, judicious selection and adjustment of extension aid and knee friction device will result in satisfactory gait at a single speed, usually the amputee's 'normal' speed.\(^1\) (Emphasis added). Though it is possible to readjust resistance mechanisms to permit proper swing characteristics at faster or slower paces, this is seldom done. In short, conventional prostheses for A/K amputees are not readily responsive to cadence or walking speed.

In early 1945, as World War II veterans were returning to civilian life, a number of above-knee amputees encountered problems with conventional prostheses which buckled under them. These problems were widely reported in Sunday supplement and other news accounts and the ensuing public concern led to official action. In January 1945, confronted with a large number of amputees in Army hospitals and with a "universal lack of standardization throughout the artificial limb industry," the Surgeon General of the Army convened a meeting to discuss requirements and specifications for developing an artificial leg which would incorporate the best features of available prostheses.\(^2\) Participants included members of the Panel on Amputations of the National Academy of Sciences-National Research Council, representatives of the Army, Navy, Veterans Administration, National

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Bureau of Standards, artificial limb manufacturers, and relevant scientists. This meeting was followed by one in March of the newly organized NAS-NRC Committee on Prosthetic Devices called for the purpose of planning short and long-range programs for meeting the existing need for devices and "to investigate ways and means of manufacturing still better appliances." The surgeons who met that summer concluded that what was needed for A/K amputees was a knee joint that would not buckle. A group of engineers met following subsequently for a year or so to determine how to respond to the needs identified by surgeons. Projects were developed for both mechanical and hydraulic knee devices.

Development work was directed to solving the stance phase problem, thus technical efforts sought to create a "knee lock" device to insure stability. Clinical results from improved fitting and alignment of prostheses, supported by the results of fundamental studies of locomotion, in most circumstances, led to substantial success in improving stance phase stability. Consequently, around 1950, the emphasis in hydraulic knee development shifted to swing phase control or to making the prosthesis responsive to the cadence or walking speed of its wearer.¹

Research and development efforts in the 1950s led to the introduction, beginning in the early 1960s, of four commercial models of a hydraulic knee. We will discuss the Hydra-Cadence Hydraulic Knee, the Dupaco "Hermes" Hydraulic Knee, the Henschke-Mauch Model B "Hydraulik" System, and the Henschke-Mauch Model A System.² The first three of these are swing phase control only, while the latter, the more technologically sophisticated device, deals with both swing and stance phase control.

Hydraulic knee mechanisms are substantially more complex technological devices than conventional A/K prostheses but offer several important advantages over the latter. Two major advantages are smoothness of swing and cadence responsiveness. As Lewis has noted:³


³Parenthetically, it should be noted that the minimum resistance level
A hydraulic mechanism swings smoothly, evenly, and consistently throughout its entire range, providing the amputee with a sense of rhythm, or continuity of movement. The amputee does not experience terminal impact or any sudden or rapid changes in the rate of swing of the leg, but rather smooth transitions from the slower portions of swing to the more rapid portions of swing phase. Once the resistance mechanism has been adjusted to provide proper resistance at the amputee's typical normal speed, changes in walking speed do not require readjustment because of the fact that the resistance to flow is velocity dependent.

There is a third advantage to hydraulic knee mechanisms, namely, their greater reliability of adjustment. Friction in conventional devices causes the "brake lining" to wear out, so readjustment is necessary from time to time to maintain a given level of resistance. Practically speaking, hydraulic devices do not wear in this way and resistance does not decline with use. We might briefly summarize these advantages by noting that in the hydraulic knee the magnitude of resistance is adjustable, the level of resistance easily can be made to vary as a function of knee position, and the device is responsive to cadence or walking speed.  

There are essentially three components to any hydraulic knee "setup"--the knee block, the shank, and the hydraulic unit. The hydraulic mechanism is clearly the technically complex portion of these devices. Development of these devices is described below, followed by an analysis of the "demonstration" effort of the VA--the clinical application studies to which all devices were subjected. Before turning to these matters, however, it is important for us to understand the prosthetics technology delivery system within which these hydraulic knee mechanisms were developed, demonstrated and diffused into use.

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1 For a hydraulic knee is normally greater than the "free knee" resistance level of a conventional A/K prosthesis. A small number of A/K amputees, therefore, may perceive a hydraulic knee to be a disadvantage because the residual resistance is greater than that to which they are accustomed.

1 See Appendix A for a pictorial and graphic representation of these devices.
II. THE PROSTHETICS TECHNOLOGY DELIVERY SYSTEM

The notion of a "technology delivery system" has been advanced within recent years as a means for describing "the complex processes by which knowledge in natural and social sciences is deliberately applied to achieve desired outputs of consumer amenities and social values." The concept refers to the patterned interactions among a number of different institutions which are directed toward the realization of knowledge application in a particular domain of public policy. In this respect, it is appropriate to speak of a prosthetics technology delivery system (TDS).

The prosthetics program of the Veterans Administration, like the entire VA hospital/health care system, exists at the institutional intersection of two worlds. It is part of the overall VA hospital/health care system, in the first instance, and it is an integral element of a larger national prosthetics system. The VA demonstration of the hydraulic knee, therefore, while serving purposes explicit to the population of veteran A/K amputees, must also be understood relative to the larger prosthetics system. It should be noted that the VA, by law, is expected to make prosthetics research results widely available so that all disabled may benefit.

The Amputee Population and the Market for Prosthetics

The number of amputees in the United States is estimated to be 1.5 individuals per 1,000 population, based upon four household surveys by the National Center for Health Statistics (NCHS) and comparison with United Kingdom data. On the basis of an estimated U.S. population at the beginning of 1975 of 212 million, there are an estimated 318,000 amputees in this country. The proportion of upper limb and lower limb amputees is 30 and 70 percent respectively, which would mean an estimated number of lower limb amputees of 222,600 for 1975.

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Not all amputees wear prostheses. The rule of thumb, based in part upon NCHS surveys, is that approximately 75 percent of lower limb amputees are prosthesis wearers. Again using 1975 numbers, this means that there are approximately 167 thousand wearers of lower limb prostheses.

How many lower limb prostheses wearers are A/K amputees? Numbers are difficult, but three surveys indicate percentages. Is it useful, though, to indicate the percentages of A/K prostheses relative to below-knee (B/K) prostheses, because this ratio has been changing over time. In a 1961-63 survey of 12,000 new amputees fitted for the first time with prostheses, 86 percent were lower limb prosthesis wearers.1 Of this latter group, 52 percent were A/K prosthesis wearers and 43 percent were B/K prosthesis wearers. A 1965-67 survey indicated that among lower limb prosthesis wearers, A/K accounted for only 41 percent while B/K was up to 53 percent.2 More recently, a 1973-74 survey indicated that this shift had continued, with 36 percent of lower limb prosthesis wearers being A/K and 59 percent being B/K.3

Each of these three surveys constituted a sample of new fittings during a given period of time, not a census of either A/K or B/K prosthesis wearers. It is possible to make some rough estimates of the size of A/K prosthesis wearers, however, on the basis of the above data and estimates. Let us compare 1961 and 1975:

<table>
<thead>
<tr>
<th></th>
<th>1961 (thousands)</th>
<th>1975 (thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. Population</td>
<td>186,000</td>
<td>212,000</td>
</tr>
<tr>
<td>A. Est. Amputee Pop.</td>
<td>279</td>
<td>318</td>
</tr>
<tr>
<td>(1.5/1000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Est. Lower Limb Amp.</td>
<td>196</td>
<td>223</td>
</tr>
<tr>
<td>(.7 of A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Est. Lower Limb Prostheses</td>
<td>147</td>
<td>167</td>
</tr>
<tr>
<td>(.75 of B)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D. Est. A/K Prostheses:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1961 (.52 of C)</td>
<td>76.5</td>
<td>86.8</td>
</tr>
<tr>
<td>1965 (.41 of C)</td>
<td>---</td>
<td>68.5</td>
</tr>
<tr>
<td>1973 (.36 of C)</td>
<td>---</td>
<td>60.1</td>
</tr>
</tbody>
</table>

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3Hector W. Kay and June D. Newman, "Relative Incidences of New Amputa-
While actual data are not available on the current population of A/K prosthesis wearers, we can say on the basis of the above estimates that the A/K prosthesis wearers in 1975 do not exceed 87 thousand, may be as few as 60 thousand, and are probably somewhere in between. Experts in the area believe that the net effect of the growing population of total lower limb prosthesis wearers offset by the declining proportion of A/K wearers is a slowly growing A/K prosthesis population.

The shift from A/K amputation to B/K amputation, it should be noted, is a secular shift attributable to several factors. First, surgeons have been educated increasingly to take the additional risks and amputate below the knee, thus saving the natural knee mechanism. Secondly, clinical results in amputation have been significantly improved through the increasing use of immediate post-surgical prosthetic fitting, further reinforcing the indications of below-knee amputation.¹

How many new A/K prosthesis wearers are there each year? The data are not available, but it is estimated that an A/K prosthesis on the average has an average life time of slightly more than 6 years. If we assume that the existing A/K prostheses have been acquired at a steady rate, then the new A/K prostheses would be somewhere between 10,000 and 14,500 per year (60,000 and 86,800 divided by 6).

The A/K prosthetics market, it can be seen, is rather small and stable. Moreover, there are a large number of different prostheses available to amputees. A 1972 Veterans Administration Program Guide to Selection and Application of Knee Mechanisms,² listed 33 commercial A/K prostheses which it had evaluated, of which only 5 were hydraulic. Hydraulic mechanisms, on the other hand, constitute a growing proportion of total A/K prostheses sold. Even so, the most sophisticated, most expensive hydraulic knee—the Henschke-Mauch Swing-and-Stance System—

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does not cost more than $250. If all new prosthesis wearers procured
the Mauch S-N-S System, the total annual sales by manufacturers to
prosthetic facilities would be only 2.5 - 3.6 million dollars.

It is also important to note, for purposes of this case study, that
the portion of the market served by the Veterans Administration consti-
tutes not more than 10 percent of the A/K prosthesis wearers and perhaps 15
percent of the purchasing dollars. The VA demonstration of hydraulic
knee mechanisms, therefore, is directed at a fairly small slice of a
modest market, though the VA is the largest single consumer in that market.

Not surprisingly, the supply side of the prosthetics market consists
of relatively few firms. One prominent figure in prosthetics suggested
that no more than a handful of manufacturing firms accounted for the
lion's share of prosthetic devices in the United States. The major firms
are: United States Mfg. Co., Glendale, California; Hosmer Corporation,
Santa Clara, California; Kingsley Manufacturing Co., Costa Mesa, Calif-
ornia; Pope Foundation, Kankakee, Illinois; and Otto Bock, a West German
firm with a distributorship in Minneapolis, Minnesota. Moreover, pros-
theses are not the main source of income for some of these firms, since their
volume of sales is quite low.

In the case of hydraulic knee mechanisms, eight or nine firms were
interested in this development in the immediate post-World War II period.
Of these, only Mauch Laboratories, Inc., of Dayton, Ohio, can trace its
activities back to that initial period. Mauch Laboratories, moreover,
though the producer of the most sophisticated hydraulic knee on the market,
is literally an outgrowth of Hans Mauch's home laboratory.\(^1\)

It should be noted that prosthetists confronted a big jump in work-
load in the mid-1960s with the advent of Medicare and Medicaid. Though
no good numbers exist, the general situation today is one in which rela-
tively few individuals pay for prosthetic devices out-of-pocket. Almost
everyone is partially or entirely covered by third-party payment, either
through private insurance of one of several programs of Federal and/or state

\(^1\)While no sustained effort has been made in this direction, the
Committee on Prosthetics Research and Development has, from time to time,
sought to interest some of the larger aerospace firms in entering the
industry. Confronted with the size of the potential market and the volume
of annual sales, these firms have always replied in the negative.
governments. The Veterans Administration, with responsibility for veteran amputees, pays out more for prosthetics on a per capita basis than anyone else. But the market, in short, is not that sensitive to price, given the extent of third-party payment mechanisms covering prosthetic devices in this society.

General Characteristics

The contemporary prosthetics technology delivery system has its historical roots in World War II. Out of the 1945 activities cited above emerged a prosthetics research program under the direction of the newly created Committee on Prosthetic Devices of the NAS. Initially supported by the Office of Scientific Research and Development, then briefly by the Army, the financial sponsorship was shifted to the Veterans Administration soon after the war as military personnel returned to civilian life. The NAS functioned in the immediate post-war years as a manager of an R&D program conducted by subcontractors, a function which was assumed directly by the VA in mid-1947. Nevertheless, one important outcome of these initial activities was that the National Academy of Sciences, through the Committee on Prosthetic Devices and its successors, came to play a major and central role in the prosthetics technology delivery system. Initially a program manager for the early R&D effort, it has always been the principal advisor and has provided a forum within which policy planning, development, and coordination for the Federal government has taken place. While agencies are free to set their own course, the major institutional participants in prosthetics have been brought together in a cooperative functioning network through the coordination of the Academy. The NAS-NRC effort has been directed to correlating research results performed at different laboratories in the country and to introducing the results of research into clinical application.¹

R&D Funders

The Veterans Administration prosthetics R&D program has occupied a major place throughout the history of the prosthetics TDS. It was an early and then sole source of Federal government support for extramural prosthetics research and development from shortly after the end of World War II

¹A chronology of the several committees of the NAS-NRC can be found in Appendix B.
until the mid-1950s. In fiscal 1975, the budget for the VA prosthetics R&D program was approximately $3.7 million. Activities supported within the program range from fundamental studies through device development, test, and evaluation, to professional education on a wide range of prosthetic and orthotic devices and techniques.

In 1955, on the basis of legislation adopted in 1954, the Vocational Rehabilitation Administration (now the Rehabilitation Services Administration of the Social and Rehabilitation Service) began a prosthetics R&D program supporting work across-the-board in scope. Today, in fiscal 1975, the RSA/SRS program is approximately $5 million.

The Army, until the early 1960s, supported work done at the Walter Reed Army Institute of Research on sophisticated upper extremity prosthetics, though more recently its mission has substantially shifted to the application of engineering to various medical problems. The Navy, through its Prosthetics Research Laboratory in Oakland, California, has supported work to develop methods and devices which could be put to use quickly in a national emergency, work which was more characterized by cut-and-try engineering in a hospital setting than by research-based engineering. The Children's Bureau and the Office of Education have supported prosthetics development and evaluation on a much smaller scale and frequently on an episodic basis. The National Institutes of Health and the National Science Foundation have supported some basic research.

R&D Performers

Research and development in prosthetics is performed by a number of different institutions, including universities, government laboratories, and private firms. The Veterans Administration prosthetics R&D program is performed in a major intramural VA laboratory—the VA Prosthetics Center in New York City, in a few VA hospitals, and by research contractors, both universities and private firms.

Several VA contracts support fundamental studies in prosthetics. Work on lower limb prostheses has been performed by the University of California's San Francisco School of Medicine and the Berkeley College of Engineering. Fundamental studies of locomotion and biomechanics at UCSF/B in the late 1940s and early 1950s, for example, led to better understanding of alignment in the stance phase and thus to the conclusion that hydraulic leg development work should focus on swing phase control.
rather than stance control. Emphasis in the development work was appropriately changed. This same group generated the data allowing determination of where the ports in the Mauch hydraulic control bushing should be located to insure the desirable relation between fluid resistance and knee flexion and timing during swing in the knee mechanism. Mauch used these design specifications without modification, and Dupaco also used them to design a simpler unit.

In the case of the hydraulic knee, all development work was performed by private firms though each had a different relationship with the VA. The work at Mauch Laboratories, for instance, where the Henschke-Mauch Model B and the Model A Systems were developed, was wholly supported by the VA. The Dupaco "Hermes" hydraulic knee was produced by the firm itself under license of the Mauch patents, the device being a simplified version of the Mauch system. The Hydra-Cadence knee was completely developed by commercial resources.

The Professional Prosthetics Community

An amputee encounters a number of professionals in obtaining and wearing a prosthesis. The surgeon who performs the amputation will prescribe for him a prosthetic device. A certified prosthetist will supply him with that device, fit and align the prosthesis, check it out after the fitting, and supervise maintenance and repair of the device. The amputee may also encounter a therapist who trains him in the use of the prosthesis.

A high amount of professional education has not always been required of prosthetists, though that is slowly changing. Those within the prosthetics TDS wishing to introduce a new device into use, therefore, have had to contend with a certain amount of skepticism from practice-oriented, empirically trained prosthetists toward the results of prosthetics research and development. Consequently, the NAS-NRC Committee on Prosthetics Research and Development, its companion Committee on Prosthetics and Orthotics Education, and the relevant Federal agencies, have directed a
substantial portion of their efforts to the education of the professional prosthetics community. These efforts have been part of a deliberate strategy to facilitate the flow of research results into clinical practice.

There are three main objectives of the educational efforts. First, there has been an effort to induce greater cooperation between surgeons and prosthetists and to encourage a more holistic approach to the related problems of surgery, wound healing, stump preparation, and immediate post-surgical fitting and alignment of prostheses. Secondly, there have been various educational efforts to increase the knowledge of new prosthetic devices and techniques among the prosthetics professional community. Finally, educational efforts have been directed to the therapist, those professionals responsible for the training of amputees in the use of prosthetic devices.

Several means have been used to achieve these objectives. One is to provide formal post-graduate education in prosthetics at three major medical schools in this country--New York University, Northwestern University, and the University of California at Los Angeles. Formal courses of one, two, or several weeks duration are offered for physicians, prosthetists, and therapists. A second educational means is through brief seminars of one day to one week in length, sponsored by the VA, and available on a tuition-free basis to participants. These seminars are more cursory than the formal course offerings of the medical schools, but cover a good deal of material in a short time.

The most significant means of reinforcing the education of the professional prosthetics community is the set of relationships which connect formal educational work with certification. Certification of prosthetists is done by the American Board for Certification of Orthotists and Prosthetists, and the educational requirements for certification include attendance at certain courses conducted by one of the three medical schools. The 1974-75 listing of courses in prosthetics and orthotics of the New York University Post-Graduate Medical School, for example, indicated that courses in below-knee prosthetics, above-knee prosthetics, and upper-limb prosthetics were open to certified prosthetists "and to those preparing for certification who have had a minimum of two years' experience in the field." Frequently, the courses at these medical schools will include information in the formal instruction on a new prosthetic device which is being introduced into use. In
this way, information about new prostheses is incorporated into the education program leading to certification.

But certain agencies, like the Veterans Administration, require that there be specific training for a particular prosthetic device before the prosthetist can provide that device to an eligible veteran. To the extent, then, that the ability to provide prescribed prostheses represents an economic incentive to the prosthetist, to that extent the TDS is organized to encourage him to seek formal training directly relevant to a specific device. General certification and that related to specific prosthetic devices is intimately connected with the formal education system in prosthetics.

Overall, the prosthetics TDS has a long history, consists of a number of institutions functioning in a highly integrated way, with closely knit personal relationships existing among the principal individuals. The institutional TDS has evolved along with the development of new prosthetic devices and can be fairly described as an evolving learning system. The scope of the TDS encompasses all prosthetic and orthotic (braces) devices, involves the participation of all relevant institutions, and spans all functions--fundamental research studies, development, demonstration, professional education and certification, and patient care.
III. THE VA "DEMONSTRATION" PROGRAM

Prosthetic device development within the Veterans Administration generally proceeds through the stages of development, clinical testing and evaluation and educational activities to promote diffusion. Development efforts proceed from a rather clear idea of the clinical needs for specific amputee impairments. Since these impairments do not change appreciably over time, the R&D efforts are directed to fairly stable problems and to the task of relating technological possibilities to those problems. Devices move from prototype model to a production model and are then subjected to clinical testing and evaluation.

It was the case with the hydraulic knee mechanisms that limited field testing preceded clinical application studies. The former is no longer routinely conducted, but the latter remains a critical feature of the device development-to-use cycle for major items. These activities of "real world" trials--field testing and clinical application studies--constitute the demonstration effort for purposes of this case study, though most emphasis will be on the latter.

If the results of a clinical application study are successful, and in the nature of things the probabilities are very high that they will be so, the Veterans Administration will accept a device "on contract". This means that if the particular prosthetic device in question is prescribed by a VA physician and provided by a certified prosthetist for any eligible VA beneficiary, the VA will pay for the cost of purchase, fitting, and maintenance of that device.

Running concurrently with the clinical application and occasionally beginning earlier in the development and field testing stages, are a variety of educational activities directed mainly to the professional prosthetic community.\(^1\) These activities, as indicated below, are designed in large measure to reduce the institutional uncertainty associated with these key professionals.

This case study is concerned with the "demonstration" of four hydraulic

\(^1\)See op. cit., Bernstock.
knee mechanisms accepted "on contract" by the VA from the early 1960s onward. These four models are the Henschke-Mauch Model B "Hydraulik" System and the Swing-N-Stance (S-N-S) System, both produced by Mauch Laboratories, Inc., Dayton, Ohio, the Hydra-Cadence Hydraulic Knee, produced by U.S. Manufacturing Co., Glendale, California, and the Dupaco "Hermes" Hydraulic Swing Control Unit, originally produced by Dupaco, Inc., Arcadia, California, now manufactured by Hosmer Corporation, Santa Clara, California. "Demonstration" for these purposes includes field testing and clinical application studies. Since demonstration activities are an integral part of the VA prosthetics R&D program, however, it is important that we give consideration to the development of these devices.

The Development of the Hydraulic Knee

Henschke-Mauch Model B. \(^1\) In 1945, near the end of World War II, Ulrich Henschke, an M.D. with a Ph.D. in Physics, and Hans A. Mauch, an engineer, began work, first in Munich and then in Heidelberg, on an artificial knee which would overcome the stability problems of above-knee amputees through the application of hydraulic principles. Their first unit was built in mid-1945. The U.S. Army Air Force supported the two men in Heidelberg until December 1946, when it transferred them to the Aero-Medical Laboratory at Wright Patterson Air Force Base in Dayton, Ohio. They were assigned other duties in Dayton until October 1947, when they were permitted to return to work on the artificial knee. Contractual support for their work, performed on an overtime basis in Mauch's house, came from the Veterans Administration.

The German team by this time had developed the design of a pendulum-controlled hydraulic stance phase unit with an elementary swing

phase. The stance control pendulum was first demonstrated before the NAS-NRC Advisory Committee on Artificial Limbs in 1948. Henschke then dissociated himself from the effort to work on other Air Force projects. Development work continued under Mauch, who worked closely with New York University to eliminate some persistent shortcomings in the units. In 1950, NYU was asked to test the first system.

Mauch had been working on both stance phase and swing phase control problems. When thinking shifted to an emphasis on swing control, Mauch was urged to devote more attention to that aspect of the problem. In February 1953, development work had proceeded to the point where the NAS-NRC Advisory Committee on Artificial Limbs suggested that two swing phase-only units be developed "to enable outside adjustment of the hydraulic swing-phase damping." By August 1953, Mauch had designed an adjustable swing-phase control device, the prototype of the Model B. It is important to note that this device was compatible with the stance control unit, Model A, on which earlier work had been conducted, and which would later be merged with an improvement over the Model B to become the Swing-N-Stance System.

Development work continued on this model and, in June 1955, at a Washington, D.C., meeting of the NAS-NRC Phase II Subcommittee, it was decided to build 2 swing control only units. Two units were fabricated, tested, and evaluated. In December 1955, the Model B was considered to have successfully completed evaluation of the developmental model and a contract was let for the production of components with which to build test models for NYU. In June 1956, the Phase II Subcommittee of the NAS-NRC CPRD concluded that the Henschke-Mauch Model B had "successfully completed the shake-down test stage of development." Later in 1958, NYU began the field testing of the Model B device.

**Hydra-Cadence Hydraulic Knee.** John Stewart, a New Zealand engineer, invented an hydraulic seal in the late 1930s which was used on almost every Allied airplane in World War II. The seal was purchased, developed, and marketed by Vickers, Inc., of Detroit, Michigan. Stewart, who had moved to the U.S. with the purchase of his invention, was given the run of the Vickers production plant and was provided with an experimental shop
of his own.

Stewart was an above-knee amputee, having lost his leg in an accident while racing motorcycles in New Zealand. His work in hydraulics, coupled with his personal need, led him to develop an hydraulic knee mechanism known originally as the Stewart-Vickers Hydraulic Leg. This device included a heel-activated hydraulic knee lock for a stance phase control, an adjustable hydraulic swing-phase damping mechanism, toe pick-up at 20 degrees of knee flexion, low hydraulic resistance to plantar flexion, and an adjustable neutral position of ankle flexion.

Stewart wanted to make this A/K prosthetic device available to all who could use it and Vickers supported him in this. Beyond permitting him time to work on the prostheses, however, Vickers put none of its own funds into development work. Shake-down testing was completed in 1950 on two units of the initial device with reasonably good results. Twelve units were then constructed for a service test, which was conducted by New York University's Prosthetics Device Study in 1951 and 1952. The results, reported by NYU in 1953, indicated appreciation of swing phase control but drew attention to problems of oil leaks. These results were supplied to Stewart and modifications, including elimination of the hydraulic knee lock with its intrinsically high pressure, were made in the device. Ten models of the revised device, now known as the Stewart Hydraulic Leg (Vickers having sold its rights in the device), were delivered to NYU in mid-1956 for field testing.

Dupaco "Hermes" Hydraulic Knee. The development of the Dupaco "Hermes" artificial knee is not well documented. The first design for the Dupaco system, which as noted above was an adaptation and simplification of the basic Mauch system, was announced in 1953. Development work and preliminary evaluation spanned a decade until, on February 11, 1963, the VA Prosthetics and Sensory Aids Service announced plans to conduct simultaneously clinical application studies of the Dupaco "Hermes" and the Henschke-Mauch Model B.

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1See Veterans Administration, Prosthetics and Sensory Aids Service, Research and Development Division, Clinical Application Study of the Hydros-Cadence Above-Knee Prostheses, (TR-2), New York, November 1, 1963.

Henschke-Mauch Model A. Though development priorities shifted around 1950 to swing phase control, Mauch continued to devote attention on a part-time, low priority basis to a device which would combine both swing and stance phase control. The compatibility of this device with the Model B facilitated its development. Financial support for the Model A device came from the Veterans Administration.

In 1958, a swing and stance control device was judged to have successfully completed the prototype model development and testing phase after several years of work. In June 1958, at a meeting of the NAS-NRC CPRD, Model A was accepted for Phase III (production model) field testing, and the assembly of models for this purpose was approved.

The development of the hydraulic knee mechanisms followed a different course for each of the three firms involved. The Mauch Laboratories development effort was entirely underwritten by the U.S. Government, for a brief time through the U.S. Air Force and then later through the Veterans Administration. Patents on the development were held by the Air Force and the VA, Mauch had a license to produce the system and the government had royalty-free rights to purchase the system from Mauch for its own use. The Hydra-Cadence knee produced by U.S. Manufacturing, was developed completely by commercial resources, and the patents are held entirely within the private sector. Dupaco's "Hermes" knee was developed from modifications to the manufacturer's prototype of the Mauch knee, and it was originally produced under license from the Mauch swing-phase patents.

The development stage for hydraulic knee mechanisms, then, can be briefly summarized. The impetus toward development emerged out of clinical needs and technical possibilities which came into focus at the end of World War II. These needs were articulated into an explicit set of object-

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2 These patents have now expired.
tives within the institutional nexus of the prosthetics technology delivery system. Original emphasis on stance control shifted to a concern for swing control around 1950, due largely to improvements in surgical procedures and in fitting and alignment of prostheses. Clinical experience was reinforced with knowledge gained from fundamental studies of locomotion and biomechanics. Several development efforts were pursued through the 1950s and a variety of technical problems associated with hydraulic mechanisms were worked out. Field testing of hydraulic knee mechanisms began in the mid-1950s.

The Field Testing Experience

From the late 1940s to the mid-1960s, New York University conducted a Prosthetic Devices Study (NYU-PDS), financed by a Veterans Administration contract, which field tested various prosthetic devices at the recommendation of the VA and the NASA-NRC CPRD. This activity constituted a distinct stage leading from development work into the VA's clinical application studies. Though now discontinued, the NYU-PDS field testing was an integral part of the demonstration of hydraulic knee mechanisms and thus we turn now to a brief discussion of it.

Hydra-Cadence.¹ Ten units of the then Stewart Hydraulic Leg were delivered to NYU-PDS in mid-1956, and eight were worn without routine servicing until January 1957. Five additional units were delivered in 1958 because of maintenance and malfunction problems of the initial devices and these were worn by amputees until June 1959. A summary report was then prepared by NYU.

About this time, Stewart decided to return to New Zealand and sold his patent on the device to United States Manufacturing Co., of Glendale, California. This firm, concluding that it would be a number of years before the Henschke-Mauch model would be available, invested its own funds to bring the device to commercialization. The Stewart device was renamed the Hydra-Cadence Hydraulic Knee, and was manufactured by Hydra-Cadence, Inc., a subsidiary of U.S. Manufacturing.

Throughout the field testing, amputee acceptance of the Hydra-Cadence knee was high. Some units functioned for extensive periods without leakage

or malfunction, though a number continued to have maintenance problems. The NAS-NRC CPRD thought the device would be highly acceptable with the establishment of proper manufacturing quality control. These views were transmitted to the Veterans Administration in 1959 and the latter, in October, announced the initiation of its clinical application study on the device.

Henschke-Mauch Model B. In December 1955, a few months before the favorable judgment by the NAS-NRC CPRD on the Model B developmental model, a contract was let for the commercial production of the parts of the system. A single prototype was assembled by Mauch from commercially fabricated parts and delivered to NYU-PDS. Two staff amputees wore this device and identified several minor malfunctions which were corrected by Mauch. Subsequently, the components for Model B were ordered for the assembly of the production models.

Five production models were then delivered to NYU for preliminary testing and evaluation to evaluate the adequacy of installation instructions, check the installation of the experimental knee-block/shank set-up under field conditions, and subjectively evaluate the swing phase of the production models in relation to the experimental model and among themselves. These were worn by 4 amputees fitted in the laboratory. It was concluded that instructions were adequate if certain clarifications were made, that the knee-block/shank had to be changed in shape and dimensions, that closer tolerances were needed in the fit between the unit's metal side strap and the knee bolt, and that the units were ready for field testing.

In March 1958, Mauch delivered 18 units to NYU with a statement of manufacturer's claims, a manufacturer's questionnaire, and a set of proposed installation instructions. The general field testing objective was to duplicate as nearly as possible the conditions under which a unit would be received, installed and delivered to an amputee for general clinical use. Specifically, the four objectives of the testing were to evaluate the installation and adjustment of the Mauch system, appraise its durability, ascertain amputee reactions to the device, and determine the reactions of participating prosthetists.

The field testing of the Mauch hydraulic knee was initiated in May 1958, with 18 subjects—7 from New York City, 6 from Chicago, and 5 from Los Angeles. Seven VA clinical facilities and 12 commercial limb shops were chosen to participate. All subjects were seen by the appropriate clinic team on seven occasions: at selection as subject; fitting at the limbshop; initial checkout and adjustment; final checkout at the end of the first month; three-month evaluation; six-month evaluation; and a follow-up visit at the end of one year of wear. Data were acquired by interviews with the subjects on five occasions, beginning with the initial checkout. Subjects were chosen to establish maximum diversity relative to age, type of limb (including stump length, socket type, and type of prior prosthetic knee), prosthesis activity level, and body build (essentially weight and height).

In an early phase, from May 1958 to April 1959, experience with some of the New York subjects and the initial units generated information which was fed back to the developer and resulted in further modification of the devices. It was revealed, for instance, that written instructions were not read by some participating prosthetists as carefully as they might be, so printed labels emphasizing certain critical aspects of the installation procedures were prominently attached to the set-up. Also it was learned that opposing surfaces did not "mate" when socket, knee-block and shank, and ankle-shin sections were aligned, but this was corrected and no further difficulty occurred after April 1959.¹

An NYU Interim Report, in April 1960, indicated that the installation of the hydraulic unit, based on instructions jointly developed by NYU and Mauch, posed no significant problems for prosthetists. Durability of the units had been improved by Mauch's modifications and the report concluded that considerable confidence could now be placed in the durability of the Mauch hydraulic mechanism.

Clinic team and prosthetist reactions were cautiously favorable. Comparisons of the Model B relative to the conventional units for which

¹Other difficulties reported included problems for short subjects, subjects with long stumps, and stability problems due apparently to the initial alignment of the prosthesis. Suggestions from prosthetists about possible cosmetic and material improvements were conveyed to Mauch.
it had been substituted were slightly favorable on gait, quite positive on performance, and neutral to mildly positive on its applicability to the general A/K amputee population.

Amputee reaction was far more affirmative on the Mauch system. Of the 18 subjects, 16 elected to continue using it rather than return to their prior mechanism at the end of the trial period. The other two were older, long-term wearers of prostheses—one had had an artificial knee for 36 years and the other for 29 years. NYU concluded that the Henschke-Mauch Model B System had successfully completed its evaluation program, could now be made available for above-knee amputees on a broad basis, and, subject to some limitations, was judged to provide "significant advantages to a broad spectrum of the above-knee amputee population."1

The Henschke-Mauch Model A.2 The NAS-NRC CPRD had accepted the Model A, predecessor of S-N-S System, for Phase III (production model) testing in June 1958. One production unit supplied to NYU in April 1959 was worn intermittently by two staff amputees for 14 months. The operating difficulties which were identified were corrected by Mauch and this unit was brought up-to-date by May 1960. Field testing began in early 1962, when Mauch Laboratories supplied the first of 18 units to NYU-PDS, along with a 1958 summary report, a statement of the manufacturer's claims, and a manufacturer's questionnaire. The purposes of the field testing were to determine the functional effectiveness, durability, and acceptance of the stance control mechanism. Acceptance was evaluated with reference to amputee assistance in crossing rough terrain, descending stairs and ramps, and recovering balance during potential fall situations.3

The swing and stance system was evaluated by bench laboratory tests, biomechanical evaluation, and analysis of the subjective reactions of amputees, prosthetists, and therapists. This field test, clearly, was more ambitious than that of the Model B, since the Model A was more sophisticated.

3Comparison of production and prototype models, consistency of production models, verification of manufacturer's claims, and determination of amputee reactions to both swing and stance phases of the device were also objectives.
Bench tests were to predict from laboratory results alone the general system performance. Various claims of the developer were verified in this way. Units were further classified into high or low resistance, and NYU suggested that this be incorporated into a designation which would aid in fitting heavy or light resistance wearers.

Biomechanical evaluation of the Model A considered five problems—criteria for effectiveness—but only two—gait pattern and adaptability to amputee needs—were reported on.\(^1\) Three means of locomotion were evaluated in the biomechanical testing—level walking, ramp descent, and stair descent, each relative to temporal, kinematic, and kinetic factors.\(^2\) This evaluation supported the conclusion that the swing and stance system more closely approximated the normal leg in level walking than did the prosthesis for which it had been substituted. In stair and ramp descent, though, the good leg was required to compensate for both the conventional and Mauch Model B prostheses to approximately the same extent as for the Model A System, although in different ways due to differences in descent techniques.

Twelve amputees were selected for wearing these units—4 of whom had previously worn the Model B and 8 who had worn conventional prostheses. The sample sought to achieve diversity in age, stump length, body build and activity level of amputees. Additional selection criteria included a successful history of wearing a conventional prosthesis, freedom from stump problems, and substantial flexing of the prosthetic knee in walking with a moderate to heavy resistance level in the conventional prosthesis.

Data from subjects were favorable to the Model A System relative to their previous prosthesis. Once set, resistance controls had little need

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\(^1\) Energy expenditure in locomotion was not analyzed. Comfort and convenience to the prosthesis wearer were evaluated only by subjective data. And the safety of the Model A was tested by the dynamic balance test but the data were not reduced and evaluated.

\(^2\) Temporal factors pertain to the rhythmic patterns of walking. Kinematic factors are those of leg motion considered independently of motion-causing forces—essentially displacement, velocity, and acceleration of the limb. Kinetic factors pertain to the impact exerted by the prosthetic device on the walking surface, for instance, vertical load and fore-and-aft shear.
for adjustment; though two pounds heavier on the average, only one sub-
ject reacted unfavorably to the weight; less effort was required for
walking; less noise was associated with the Model A system; maintenance
requirements tended to be less; severe temperature changes did not require
resistance adjustments; cosmetic problems were not reported; stumbles
and instabilities were reduced dramatically from a noticeable to a negli-
gible level after installation and proper training; ability to walk at
a wide range of speeds and to easily change speeds was improved; stair
descent performance was improved for seven subjects.

Prosthetists commented that the sample was highly selective, using
men between 25 and 40 years of age who were using or potentially could
use a good deal of knee friction in their conventional devices. The
residual resistance in the knee at the lowest setting, however, while
undesirable for low friction users, tended to be offset over time by
users of hydraulic artificial knees. The knee block-shank was easy to
install and durable, and the Swing-N-Stance Control unit itself was simple
to install and replace. Durability was good. It was noted that the
majority of the amputees reacted favorably to the new device.

Therapists reactions indicated that the training procedures for the
swing phase were standard and differed little from other fluid controlled
knees. Subject difficulty in learning the procedures was considered
normal. It was observed, however, that it took subjects "several visits
and a good deal of motivation and private practice" to master the new
methods of stair and ramp descent, due basically to the "unlearning"
required of an amputee. Though some were subjects in this test, it was
felt that a new amputee, trained initially to the new system, would experience
far less difficulty in its use, since he brought no acquired fear of knee buckling.

Five kinds of malfunctions occurred: (1) metallic clicking noises;
(2) inadvertent locking; (3) intermittent loss of swing resistance accom-
panied by excess terminal deceleration; (4) excess and/or intermittent
kick-strap action; and (5) fractured knee adjustment screw. Modifications
of the production process eliminated these problems, however, and the over-
all record of the 16 systems tested was quite satisfactory. NYU concluded:
"At its present state of development, the unit is performing consistently
and is substantially trouble free."
The NYU-PDS field testing of hydraulic knee mechanisms was an activity which linked the development effort with the VA's clinical application studies. By means of assigning a small number of devices to staff amputees for wear, malfunction and maintenance problems were identified, information was relayed to the manufacturer, and corrective modifications were made. Further information was gained through these tests about amputee reaction to the new prostheses, though not on an as extensive a scale as the clinical application studies would provide. Reactions of the professional prosthetics community were also obtained, again on a lesser scale that through a clinical application study.

In the mid-1960s, the contract with the Prosthetic Devices Study of New York University was phased out. Professional judgment was less than enthusiastic about the quality of work performed. The VA, moreover, through the Prosthetics Center in New York, had established essentially all the engineering testing capability which was needed. (The NYU-PDS activity, interestingly enough, had been housed in the same building in New York as the VA Prosthetics Center and actually used VA testing equipment.)

We turn now to an appraisal of the clinical application studies, where emphasis on the whole has been weighted more heavily on user acceptance, professional community reaction, and educational aspects than on matters of reducing technical uncertainty.

Clinical Application Studies

The Veterans Administration has conducted a clinical application study for each of the hydraulic knee devices considered in this case study—the Hydra-Cadence, Dupaco "Hermes", Henschke-Mauch Model B, and Henschke-Mauch Model A. The table on the following page summarizes the information on these studies with respect to dates of VA authorization, number of amputee subjects, number of participating VA clinic teams (each one of which is in a different city) and commercial limb shops, and test wear period for the device for each subject. In addition, the dates of the relevant reports are indicated.

The major purpose of a VA clinical application study for any device is to determine the desirability of placing the device "on contract for issuance
<table>
<thead>
<tr>
<th>Device Name</th>
<th>VA CAS Authorized</th>
<th>Amputee Sample</th>
<th>VA Clinic Teams</th>
<th>Commercial Limb Shops</th>
<th>Test Wear Period</th>
<th>Reports</th>
<th>VA &quot;On Contract&quot;**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydra-Cadence</td>
<td>10-19-59</td>
<td>100</td>
<td>27</td>
<td>68</td>
<td>1 year</td>
<td>3-15-61</td>
<td>4-2-62 11-1-63</td>
</tr>
<tr>
<td>Henschke-Mauch</td>
<td>2-11-63</td>
<td>36</td>
<td>14</td>
<td>31</td>
<td>6 mos.</td>
<td>2-1-64 12-1-64</td>
<td>TR-3 1-2-62</td>
</tr>
<tr>
<td>Model B</td>
<td></td>
<td></td>
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<tr>
<td>Dupaco &quot;Hermes&quot;</td>
<td>2-11-63</td>
<td>41</td>
<td>13</td>
<td>32</td>
<td>6 mos.</td>
<td>2-1-64 1-4-65</td>
<td>TR-4</td>
</tr>
<tr>
<td>Henschke-Mauch</td>
<td>10-66</td>
<td>33</td>
<td>12</td>
<td>25</td>
<td>6 mos.</td>
<td>Fall 68 BPR 10-10</td>
<td>Rec. by BPR 10-10</td>
</tr>
<tr>
<td>Model A</td>
<td></td>
<td></td>
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</table>

* These two devices were studied concurrently and involved essentially the same VA clinic teams and commercial limb shops.

** The actual date of the "on contract" decision is indicated only for one device; the others were recommended for "on contract" in the reports indicated and these were acted upon favorably.
on a prescription basis to disabled veterans.\textsuperscript{1} The "on contract" decision was recommended by each of the four clinical application studies and was favorably acted upon by the Veterans Administration. The primary criterion for an "on contract" recommendation by a clinical application study is amputee acceptability of the prosthetic device being tested. Therefore, the criteria for the selection of amputee subjects is of interest to us.

Similar criteria were used for subject selection in each of the four clinical application studies. These criteria can be grouped in three general categories—institutional, clinical, and test-related. The most significant institutional criterion was that the subject be "a male, service-connected veteran who, at the time of prescription, would normally have been entitled to a new prosthesis under established policies." Other institutional criteria were that the subject have a usable spare conventional prosthesis, understand that a test prosthesis might not be available after completion of the test, agree to return the device if he withdrew from the study or was rejected from it after issuance of a device, not be a commercial limb shop employee, and be willing to be photographed for publication purposes.

The clinical criteria required that the subject: be an A/K or hip disarticulation amputee with no significant stump problems, be an active wearer of a conventional prosthesis,\textsuperscript{2} with a relatively satisfactory prosthetics history, emotionally stable, and strongly motivated to participate in the study. The test-related criteria for subject selection were that the amputee refrain from adjustments to the prosthesis himself during the test wear period and continue to live during this period within the jurisdiction of the clinic team.

Subject selection was performed by the participating VA clinic teams using guidelines prepared by the Research and Development Division of the VA Prosthetics and Sensory Aids Service. Under these circumstances, the subject population obviously did not represent a random sample of the

\textsuperscript{1}Op. cit., Lewis and Bernstock, 1968.

\textsuperscript{2}This was relaxed late in the Model A study to include "a recent amputee who had never worn a prosthesis."
total U.S. A/K prosthesis wearers. The primary sampling "bias", however, was in the direction of selecting a subject population for whom the new prosthesis was likely to be suitable. Later one could seek to extend the use of the new device to individuals who were more "marginal" in clinical terms.\footnote{This strategy of subject selection is not at all uncommon in the demonstration of a new clinical innovation in medicine.} In this way, subject selection was clearly directed to insuring a successful demonstration of the given prosthetic device through the clinical application study.

The sample size needs were not discussed in the clinical application studies, but apparently subsequent studies benefited from the initial evaluation of the Hydra-Cadence device. Whereas that sample involved 100 subjects and a test wear period of one year for each, successive studies included 36, 41, and 33 subjects for a test wear period of six months in each study.

The 1960–62 study of the Hydra-Cadence device set the framework for the other studies in design. The basic logic was a "before" and "after" evaluation with a thorough evaluation of the subject's performance on a conventional prosthesis preceding the test period. Evaluations of the subject's experience with the test device were obtained at regular intervals throughout the test period. The general impression of the clinical evaluation studies is that amputee reaction, which was favorable in each instance, did not constitute a major source of uncertainty at the outset of the test.

Another important purpose of the clinical application studies was the education of the prosthetics professional community. As the VA report on the Hydra-Cadence hydraulic knee noted:

\footnote{Op. cit., TR-2.}

In addition, and of perhaps equal importance, were the educational by-products of the study. The principles of fluid controlled mechanisms for above-knee amputees became more meaningful to the prosthetists from the 68 facilities engaged in fitting the Hydra-Cadence prostheses, to the physicians, therapists, and Prosthetic Representatives of the 27 participating clinic teams, and indeed, to the staff directing the study.
The clinical application studies involved two institutional groups—the VA clinic teams and the prosthetists associated with commercial limb shops. There are within the Veterans Administration a number of Orthopedic and Prosthetic Appliance Clinic Teams—35 formally designated and another 50 having an informal designation. These teams consist of physicians, usually surgeons, involved in amputation of limbs and in the prescription of prostheses, prosthetists concerned with post-surgical fitting and alignment of prostheses, and therapists dealing with the pre-fitting evaluation of a subject and his training in the use of a device. In the clinical application studies, clinic teams were responsible for selection of subjects and participating commercial prosthetic facilities, gathering of data, and general administration of the study.

The number of clinic teams involved in the four successive studies was 27, 14, 13, and 12. The total number of teams used was 32, with 3 new teams added in the second clinical study and two in the last study. Five VA institutions were involved in each of the 4 clinical application studies. These were: VARO/VAH Atlanta, Georgia; VAOPC Boston, Massachusetts; VAH Denver; VARO/VAOPC Philadelphia, Pennsylvania; and VAH Seattle, Washington. Six institutions were involved in three tests each: VAH Buffalo, New York; VAH Cincinnati, Ohio; VAH Memphis, Tennessee; VARO/VAH New Orleans, Louisiana; VARO Pittsburgh, Pennsylvania; and VARO Portland, Oregon. Thus, the clinical application studies were an educational means for bringing direct personal knowledge of hydraulic knee mechanisms to widely scattered VA personnel.

The commercial prosthetic facilities were the other institutional participants in the clinical application studies. These firms are engaged in the selling, fitting, alignment, and maintenance of prosthetic devices. There were 68, 31, 32, and 25 such facilities involved in each of the four clinical application studies and a total of 88 overall. Among the criteria employed by the VA clinic teams in selection of a participating prosthetic facility, one of the most important was that it "have a prosthetist who has attended a university-level above-knee prosthetics course" who would be responsible for the fitting and alignment of the hydraulic device. Other criteria included a willingness to follow the manufacturers' guidelines in the installation of the prosthesis and to make only authorized
adjustments to the device. Among the participating limb shops, 16 were local units of a larger organization. J. E. Hanger, Inc., for instance, had 10 different limb shops in that many cities participating in the studies, while the Winkley Artificial Limb Co., Snell's Limbs and Braces, Inc., and Modern Limb and Brace Co. each had two facilities participating in the studies. Overall, the number and distribution of these limb shop facilities meant that the clinical application studies were instrumental in the education of the professional prosthetics community.

The incentives to a commercial limb shops to participate in a clinical application study should be mentioned. They include an opportunity to become familiar with a new prosthesis at no additional cost. More importantly, participation in such a study exempts the prosthetist in that limb shop from the educational requirement later imposed by the Veterans Administration that he have formal training in that device before he can provide it to a veteran for whom it has been prescribed. Such training is required by the VA of all non-participating prosthetists subsequent to an "on contract" decision.

This brings us to consideration of one of the main purposes of the clinical application studies, namely, the education of the professional prosthetics community to a new prosthesis. The observations of A. Bennett Wilson, long-time executive director of the NAS-NRC CPRD, on these studies are useful to understanding this purpose.¹ These clinical trials were mainly an introduction of a new device into the field, a device whose functions were appreciated by healthy amputees. The trials were as much an education program as anything, a program directed to the clinic teams, to the M.D.'s running amputee clinics, the prosthetists prescribing devices, the therapists training amputees. It was an effort to educate them in how to apply these devices properly. If you don't do it right, then you lose the benefit of the device.

In short, the "demonstration" effort was less directed to the reduc-

¹ Telephone interview with A. Bennett Wilson, Krusen Center for Research, Temple University, June 23, 1975.
tion of technical uncertainty about a new device than to the reduction of uncertainty about its acceptance by the professional prosthetics community. We shall elaborate this in the next section where our conceptual framework is analytically applied to this case.
IV. THE APPLICATION OF OUR CONCEPTUAL FRAMEWORK

We have defined demonstrations as directed to the reduction of uncertainty or, conversely, the production of information, in five different dimensions. Here we examine the hydraulic knee experience in light of uncertainty reduction for each of these dimensions.

Technological Uncertainty

The "demonstration" of hydraulic knee mechanisms, that is, the NYU-PDS field testing and the VA clinical application studies, is an integral part of an institutional program which ranges from research and development through test and evaluation to introduction of a device into widespread clinical use. The development of a prosthetic device, moreover, involves a continuous interaction between the developer, the prosthetics TDS and the Veterans Administration, as exemplified by this case. A constant stream of evaluative data identifying maintenance and malfunction problems of a given prosthesis is produced which is fed back to the manufacturer so that modifications and adaptations can be made up to and through the initial production run of devices. It is generally the case, therefore, that the major technical problems associated with a given device are relatively well resolved prior to the initiation of a clinical application study.

Device development in prosthetics, furthermore, occurs within a relatively well understood R&D agenda, developed by full participation of all members of the TDS and coordinated in the large by the NAS-NRC's CPRD.\(^1\) The R&D agenda, it should also be recalled, is shaped with respect to very specific limb impairments. Thus, the problems to which the R&D effort is addressed to not change appreciably over time.

It is worth observing that much less reliance is placed upon laboratory simulation of device use conditions today than once was the case. This is due to the realization that it was very difficult to adequately

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\(^1\) See, for example, National Academy of Sciences, Committee on Prosthetics Research and Development, Rehabilitation Engineering: A Plan for Continued Progress, Washington, D.C., April 1971.
simulate the many conditions under which devices would be used by individual A/K prosthesis wearers. Problems of dust, degree of care, etc., are such that the conclusion was reached to rely more heavily upon the clinical application study for knowledge about the reliability and maintenance of A/K prostheses. In this respect, the "demonstration" is important at reducing technical uncertainty.

In the main, however, the development phase is where technical uncertainty is reduced, not the demonstration phase, within the VA prosthetics program and for the prosthetics TDS. That general observation pertains to the hydraulic knee mechanisms as well, even though these prosthetic devices represented a major technical advance in A/K prostheses. But by the time a device reaches the point where it is authorized for a clinical application study, most of the technical problems have been resolved.

Cost Uncertainty

Cost uncertainty reduction does not loom large as a concern of the "demonstration" efforts in connection with hydraulic knee mechanisms. The Veterans Administration is not greatly concerned about cost for any particular device, viewing a given prosthesis mainly in terms of capability extension for the amputee. Data on cost per amputee, moreover, indicate that the VA spends more per individual on prosthetics than is spent for other non-veterans with comparable problems.

The VA did a brief cost-benefit analysis of the prosthetics research and development program in 1968, twenty years after it had been initiated. During this period, the average unit cost of artificial limbs and repairs more than doubled; 1968 costs were 116.5 percent of 1948 costs. Expenditures per amputee, however, which were $94.72 in 1948, rose only 29 percent to $122.27 in 1968. Had they risen as fast as the unit cost of artificial limbs and repairs, they would have been $205.07 per amputee in 1968. Total twenty year program costs were actually $47 million, whereas they would have been close to $76 million had program expenditures grown at the same rate as the unit costs of limbs and repairs.

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The difference between actual experience and that which might have been is attributed to several contributions of the prosthetics research program. First, artificial limbs in 1968 were lasting about twice as long then as those being replaced in 1948. Second, advanced clinical knowledge about prescription, checkout, and amputee management has improved fit and function of initial prostheses and has led to a reduction in premature replacement. Finally, VA clinic teams are increasingly more prudent in requiring a spare prosthesis for each amputee based upon knowledge gained about patient management. Cost reduction, therefore, is a more general aspect of the VA prosthetics program rather than a specific objective of the "demonstration" activity.

Demand Uncertainty

The amputee population, including the A/K amputee population and the A/K prosthesis wearers, both for non-veterans and for veterans, is relatively well-understood, despite the paucity of demographic data. The demonstration of a particular prosthetic device, therefore, has no effect on reducing uncertainty about the size of the potential market.

Amputee acceptance of a prosthesis, however, is a critical factor about which a clinical application study generates information. And amputee acceptability is essential if a device is going to become widely used. It would appear, however, that confidence in a given prosthesis is fairly high at the outset of a clinical application study, not only with regard to technical problems but with respect to user reaction. In large part, this is due to the selection of subjects for whom there is a prima facie basis for prescription, that is, subjects likely to find the new prosthesis a suitable device for them. Later there is a cautious expansion of prescription criteria.

Institutional Uncertainty

Institutional uncertainty stemming from the potential reactions of VA clinic teams and prosthetists in commercial limb shops to a given prosthetic device is one of the primary targets of the clinical application study. Education of the professional prosthetics community is essential to the widespread use of a given new device.

Historically, prosthetists have not been highly trained professionals
and relatively few have had any experience with research and development in prosthetics. One objective of the prosthetics TDS, therefore, has been to bridge the gap between the prosthetics R&D community and practitioner prosthetists. The Committee on Prosthetic-Orthotic Education of the NAS-NRC, a companion to the CPRD, has promoted the upgrading of training required for prosthetists for a long period of time. In conjunction with the American Orthotics and Prosthetics Association (AOPA), the trade association; the American Academy of Prosthetists and Orthotists (AAP0), the professional organization; the NAS-NRC; and the entire TDS influenced the upgrading of training. Most importantly, the TDS has evolved so that certification of prosthetists by the American Board for Certification of Orthotists and Prosthetists is linked to the formal education in prosthetics offered by the three medical schools—NYU, Northwestern, and UCLA.

Beyond general certification, agencies like the Veterans Administration and individual state rehabilitation agencies require that prosthetists be qualified or certified to provide certain prosthetic devices. This specific certification usually requires a formal education program which is explicitly addressed to the device in question. One benefit of a clinical application study to a participating prosthetist is that he is exempted from this specific educational requirements. All other prosthetists, however, wishing to provide such a prosthesis to veteran beneficiaries of the VA, are required to secure such formal training. This training, like that required for general certification, is typically provided by the three medical schools.

Institutional uncertainty associated with the reaction of the prosthetics community to a new prosthetics device, therefore, is reduced in some measure by a clinical application study. It should be noted, however, that institutional uncertainty reduction is a function which is shared by other activities of the prosthetics TDS beyond that of a VA clinical study.

Uncertainty About Externalities

The effects of a prosthetic device are limited to the wearer of the device. Relatively few externalities are generated by prostheses and those that are generated are limited to the immediate circle of family, friends, and associates with whom the amputee normally interacts. The
demonstration effort via the clinical application study does not direct itself to generating information on this matter, though it can be assumed that an improved device for an amputee has external benefits which are realized by those around him.

A successful VA clinical application study increases the likelihood of the acceptance of the device by other agencies serving the non-veteran A/K amputee population. State vocational rehabilitation officials tend to favor an "on contract" device. Other agencies, like Public Health Service hospitals, buy prostheses which are under VA contract. Local prosthetists who have "learned" about the device at VA expense see less risk in providing such a device to a non-veteran client. But we have not carried our analysis of this point very far in terms of actual data on this question.
V. LESSONS FROM THE HYDRAULIC KNEE DEMONSTRATION

There are several characteristics of demonstrations within the VA prosthetics research program which are of general interest.

- Demonstrations, field testing and clinical application studies, are an integral component of an agency research-to-use strategy which spans a continuum from fundamental studies through device development, test and evaluation, manufacturing quality control, professional education and certification, to clinical use.
- Demonstrations within this overall strategy are focused on linking device development activity with the introduction of a new prosthesis into clinical practice and use.
- Demonstrations can be flexibly applied to new prostheses emerging from the VA's own prosthetics research program, as in the case of the Mauch hydraulic knee mechanisms, or to devices emerging from the development efforts of private firms.
- VA demonstration activity, and the entire VA prosthetics research program, is embedded in a larger prosthetics technology delivery system which is relatively free from immediate political intervention, strongly goal-oriented, serving an identifiable client group, and performing overall functions of goal setting, management, and evaluation at every stage of activity. This prosthetics TDS, moreover, includes all the relevant Federal agencies, coordinating groups, educational institutions, prosthesis prescribers, providers, and trainers, professional associations, certification agencies, and commercial manufacturers.
- Demonstration activity shares the tasks of uncertainty reduction with other activities in this overall VA research-to-use strategy and with other institutions in the prosthetics TDS.
- The indicated role for demonstrations which emerges from this case study, therefore, is one which is critical though modest in
regard to uncertainty reduction.

Technical uncertainty in the prosthetics device development is reduced primarily through the R&D program, in this instance that of the VA prosthetics research program. Technical problems, moreover, are essentially constant and well understood, facilitating the development of an R&D attack upon them. Only in the area of reliability of a new device under conditions of actual use by amputees is there any degree of technical uncertainty for which the demonstration is best suited to produce needed information. In the main, however, the technology of a new prosthetic device is ready to be tested by the time the Veterans Administration undertakes a clinical application study.

Uncertainty about costs has typically been resolved through the VA medical system and the prosthetics TDS rather than by a given demonstration. If successful, as a VA clinical application study normally is, it is understood that a prosthetic device will be recommended for an "on contract" decision. This means that the VA will pay for the device if it is prescribed for veteran beneficiaries. It further means that other third party financiers will be likely to pay the costs for such a device if prescribed by a physician for a non-veteran subject. Cost considerations, therefore, are minimized for the VA demonstration by the prior commitment of the VA to pay for "on contract" devices, and by the extensive amount of third party payment for prostheses. On the other hand, the diffusion of a prosthesis approved by the VA, but costly in the judgment of other third party payors, may be constrained if the latter refuse to pay for the device. Cost considerations, however, are resolved within the general institutional context of the Veterans Administration and the prosthetics TDS and not through the VA demonstration effort.

Responsibility for reducing uncertainty about demand is partially born by the VA demonstration in which user acceptability is definitively ascertained. On the other hand, the size of the potential market for a given class of prosthetic devices is well-known, and there is general information about the potential demand for a given prosthesis which is rather well understood in advance of a demonstration.

Institutional uncertainty, while a major target of a VA clinical
application study, is offset in many ways by the nature of the prosthetics TDS. The TDS, for instance, is capable of introducing non-incremental technical changes in prostheses with relative ease because little institutional adaptation is required. As long as relative advantage to the wearers of prostheses can be demonstrated, no fundamental changes in the way of doing business are called for by the VA clinic teams or prosthetists associated with commercial limb shops.

The professional prosthetics community as a target audience, however, deserves some additional comment. The diffusion of a prosthetic device into widespread clinical use is controlled in large measure by those involved in prescribing devices, fitting and aligning amputees with prostheses, and training amputees in their use. In this respect, prosthetic devices are similar to most therapeutic innovations in medical and health care.

The "size" of a demonstration is determined in part by the educational nature of the clinical application study. A sample must be drawn which is representative of the patient population, adequate for a production run by the manufacturer, and sufficient to provide educational opportunity for VA clinic teams and commercial limb shops. Sample size is therefore coupled with site selection, for which the requirements are that the study be nation-wide in scope, include level and hilly terrain, tropical or mild and wintry climates, large and small cities and rural areas. These requirements, though, are consistent with the distribution of the study in a way resulting in the education of the prosthetics community.

Again, it should be noted that the prosthetics TDS is so organized that the educational efforts of a given VA clinical application study do not stand alone. While participating prosthetists are exempted from the requirement of formal education specific to the device in question, other educational efforts are addressed to the non-participating community, both by the VA and through the formal educational programs offered by NYU, Northwestern, and UCLA medical schools. The latter, moreover, are officially linked to certification requirements of prosthetists, thus creating a strong incentive for them to understand the operation of a new prosthetic device. In short, even in one of the key uncertainties to which the demonstration is addressed, namely, the professional prosthetics
community's reaction to a device, reduction of that uncertainty is shared between the demonstration and the other diffusion-oriented activities of the TDS.

There are strong incentives for the individual institutions throughout the prosthetics TDS to insure successful introduction of new prostheses. Thus, the clinical application study has high advance probability of success. The Veterans Administration, with its statutory obligation to care for veterans, especially those with service-related disabilities, is strongly committed to providing prostheses for veterans who are amputees. Manufacturers, at the point of a clinical application study, are on the threshold of an "on contract" decision and access to a slice of the prosthesis-wearers market. Cooperation between the VA and manufacturers is typically strong involving a close look at the adequacy of written instructions to prosthetists for device installation, preparation of manufacturer's manuals, etc. Since a successful VA study may facilitate access to the potentially much larger non-veterans market, this obviously provides manufacturers with an incentive to facilitate the demonstration. But the Veterans Administration is also provided an incentive for this same reason, since it is obliged by law to seek the diffusion of devices generated for veterans to the non-veteran population.

Cost sharing in the demonstration phase is not particularly significant within the context of prosthetic devices. Cost sharing does occur in various ways in device development, as noted earlier. It would appear in the case of the hydraulic knee that cost sharing was greatest where the technology was most complex, that is, in the case of the Henschke-Mauch Model B and the Model A, and least in the case of the Hydra-Cadence Hydraulic Knee.
REFERENCES


Appendix A

ILLUSTRATIONS OF HYDRAULIC KNEE MECHANISMS
FROM STEWART—VICKERS TO HYDRA—CADENCE MODEL D

UNITS

STEWART—VICKERS with YIELDING KNEE LOCK

MODEL A

MODEL B

MODEL C

MODEL D

WITH HYDRA—CADENCE

COVERS

STEWART—VICKERS

MODELS A, B, C

MODEL D

FEET

STEWART—VICKERS

MODELS A, B

MODELS B, C

MODEL D

FIGURE 1

FIGURE 2

Dupaco "Hermes" System

DUPACO "HERMES" SYSTEM

Fig. 3—Full extension at start of flexion swing.

Fig. 4—Start of extension swing.

Fig. 5
THE HYDRAULIK UNIT

Fig. 6
THE "HYDRAULIK" SET UP

Fig. 7
CROSS SECTION OF THE
HENSCHKE-MAUCH HYDRAULIC SYSTEM

Fig. 8—Henschke-Mauch HYDRAULIK Swing and Stance Control Unit, Model "A."

Fig. 9—Wooden setup for the Henschke-Mauch HYDRAULIK Swing and Stance Control Unit, Model "A."

Appendix B

CHRONOLOGY OF PROSTHETICS COMMITTEES
NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL

1944 Committee on Sensory Devices established in Office of Scientific Research and Development at the request of the U.S. Army Surgeon General

1945 Committee on Sensory Devices transferred to the NAS-NRC
Committee on Prosthetic Devices established as a joint committee of the Division of Medical Services and the Division of Engineering (April)
Committee on Prosthetic and Sensory Devices established, combining the functions of the two previous committees (September)
Board for Prosthetic and Sensory Devices established with two standing committees, Committee on Prosthetic Devices and Committee on Sensory Devices (November)

1946 Board dissolved but two committees continue to function; Committee on Prosthetic Devices renamed Committee on Artificial Limbs

1947 Committee on Artificial Limbs renamed Advisory Committee on Artificial Limbs

1948 Committee on Sensory Devices transferred from Division of Engineering to Division of Anthropology and Psychology, NAS-NRC

1955 Prosthetics Research Board established with Committee on Prosthetics Research and Development and Committee on Prosthetics Education and Information

1959 Board terminated but the work was carried on by two committees
Committee on Prosthetics Research and Development was reorganized (July)

1963 Committee on Prosthetics Education and Information renamed Committee on Prosthetics/Orthotics Education
PHASE II CASE STUDY INSTRUMENT

by

Edward A. Merrow
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</tr>
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I. SAMPLING CRITERIA FOR PHASE II CASES

DEFINITION OF DEMONSTRATION PROJECT

1. **Support by federal funds.** At least some portion of the cost of the project must have been borne by the federal government.

2. **Involvement of civilian sector.** This excludes space and defense projects because the federal government is the potential adopter. In addition, we wish to exclude in our Phase II cases other "closed TDS" cases, such as the Artificial Knee demonstration of the VA. This is because when the government is developing a technology for its own use, we lose many of the characteristics of market adoption decisions (either by users or manufacturers) which are most interesting from the viewpoint of our study.

3. **Stimulation of technological changes involving hardware.** This is to cut out pure process, organizational, and social change demonstrations. One of the primary foci of every case is on a hardware technology.

4. **Significant private sector involvement.** It is not clear that this criterion cuts out anything. The only conceivable case this could affect would be one in which government(s) not only used the innovation but also were to be the producers of the hardware, a rather unlikely circumstance.

5. **Operation in a real world environment** to test the receptivity of the environment to the technology as well as the technology itself. Other research and development activities such as field trials are sometimes conducted in a real world environment rather than a laboratory or test bed. But these activities are aimed at gaining information about the technology and technology-related costs alone. A demonstration on the other hand has been described as a "field test that tests the field."
We have decided to include some field trial projects in our corpus of Phase II cases in order to more clearly delineate the distinction between field trial and demonstration activities, and to aid in refining our guidelines for federal agencies to be included in the final report. Although field trials will be included, they will not be analyzed in the same terms as demonstration projects.

6. Concentrating on Successes. For demonstrations directed at producing new information, we want to concentrate on cases which were "information successes" that is, projects which prima facie appear to have produced enough information to allow potential adopters to make decisions pro or con on adopting the technology.

The following criteria should be used to establish a prima facie case for information success.

A. Review documentation, especially any evaluations of the project.
B. Ask the federal agency personnel involved and the local operating agency personnel if they consider it an information success by our definition. (This is a negative screening device; if they say "no," then we should believe them; if they say "yes" go on to number three.)
C. Find out from the federal office or operating agency what leading potential adopters the information has been disseminated to. Inquire of one or two of the potential adopters whether the information from the demonstration has enabled them to make a decision either way on the adoption of the technology.

For demonstrations which appear to be of an exemplary sort, i.e., demonstrations of technologies which have already been applied to the given use, application success is necessary for inclusion in our Phase II list. Use criterion C, above. If you know of a demonstration project aimed at institutional change which appears to have been successful in generating those changes (and even better, leading to diffusion) please bring it up for consideration. We wish to include an institutional change demonstration in the Phase II cases to add strength or refute our
tentative conclusion that they do not seem to have the desired results if we can find one.

The six criteria above are essential ones for any case we take up in Phase II. Number six will be relaxed only if we cannot come up with enough successes. The following characteristics are desirable.

PREFERRED CHARACTERISTICS

1. Length of history since demonstration became operational. Longer is better because it allows us to be more confident of our conclusions about the diffusion of the technology. Note that this criterion is more important for cases which appear not to have diffused, then it is for cases showing significant diffusion.

2. Availability of documentation. Given the severe time and budget constraints that we are working under in Phase II, good documentation such as evaluations and reports may be essential to getting the cases done accurately in a short period of time. The availability of documentation may also be important in lending credibility to findings gathered in such a short period of time.
II. BASIC INFORMATION LIST

NAME OF DEMONSTRATION PROJECT:

SITE:

FEDERAL FUNDING AGENCY:

OPERATING AGENCY:

OTHER ORGANIZATIONS INVOLVED; (Include Role)

PROJECT LIFE:
   Federal grant or contract date
   Demonstration operations began
   Demonstration (or federal funding) ended

COST: (Total)
   Federal share:
   Non-federal share (if any):
   Profit-making firms (Specify)
   Non-Profit organizations or Agencies (Specify)

AUTHORIZATION FOR FEDERAL FUNDING:

TARGET AUDIENCES:
   Potential Adopters:
   Potential Manufacturers of major technological components or system:

   Potential Users: (If relevant)
   Regulatory Agencies: (If relevant)
   Other:
III. GOALS AND TYPE OF DEMONSTRATION

It is important to distinguish a demonstration project per se from a larger program of which the demonstration may be a part. The goals below should be goals of the demonstration project, not the program.

On the basis of our Phase I case studies we delimited four types of goals for demonstration projects in addition to the diffusion goal. These are not, of course, mutually exclusive. In the space below, indicate under each category the federal funding agency's for the demonstration project and their relative importance.

A. Was the diffusion of the technology an explicit goal of this demonstration? The word "diffusion" will probably not occur very often, but it has a host of synonyms which may appear in the project's documentation. Please quote and cite the source of your conclusion about diffusion as a goal.

<table>
<thead>
<tr>
<th>(Circle one)</th>
<th>Yes</th>
<th>No</th>
<th>Unable to ascertain</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOURCE:</td>
<td></td>
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</tbody>
</table>

B. High political or policy goals, e.g., "Atoms for Peace" etc.

- Primary
- Secondary
- Not Present

C. The production of new information about the innovation, and in particular information regarding:

1. The technology:
2. Costs:
3. Demand for the technology or its output
4. Institutional and/or organizational changes induced by the innovation's adoption
5. Externalities created or eliminated by use of the innovation
D. The communicating of existing information about the innovation ("exemplification")

E. Attempts to change the institutional environment in which the adoption of the innovation would take place, e.g., attempts to change regulatory practices, the concentration of an industry, attempts to create new industrial capacity, etc.

Leaving aside high policy goals, which of these goals seemed most important:

- Production of new information
- Exemplification
- Institutional Change

If for any reason your case does not seem to fit these types, explain in detail.
IV. ORIGIN OF DEMONSTRATION IDEA

The idea for a demonstration means the idea for the specific device, system, or process to be demonstrated. It does not refer to basic research and development leading to the demonstration.

Our central concern is to know if the impetus for the demonstration of a particular technology arose from the local (user) level or from decisions of the Federal Government. Our hypothesis is that locally generated demonstrations are more responsive to real user needs than federally generated ideas.

"Locally Generated Idea"

Idea for demonstration initiated by local organization(s) to be funded under federal agency's broad mandate, e.g., unsolicited proposals.

Local organization responds to broad federal invitation, e.g., RFP issued to address some general problem, without specifying a particular technology

"Federally Generated Idea"

Local response to specific federal request, e.g., RFP issued for proposals dealing with a particular kind of technology specifying the sorts of devices, systems or processes to be demonstrated.

Federal initiative, e.g., an organization is requested to operate a demonstration under contract or grant, technology specified by a Federal agency

Other: (If you have difficulty placing the case, explain the circumstances)

_____________________________________________

_____________________________________________

_____________________________________________

_____________________________________________

No Data
V. THE NATURE OF THE TECHNOLOGY DELIVERY SYSTEM (TDS)

A TDS refers to the set of functions, often embodied in sets of organizations, and the relationships between them which directly influence the process by which new technologies are introduced and passed into use. The structural components of a TDS include the R&D funder, the R&D performer, the goods producer, goods purchaser, the end user, and often financial and regulatory organizations. We are concerned primarily with the TDS "downstream" from R&D, i.e., the designers and manufacturers, the purchasers and users and regulatory and market intermediary organizations where relevant. Our hypothesis is that demonstrations which are linked to a strong existing TDS enjoy greater diffusion success.

1. Define the components of the TDS which would commercialize the innovation in this case.

<table>
<thead>
<tr>
<th>TDS Component</th>
<th>Was the TDS component included in the demonstration? (circle)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes  No</td>
</tr>
<tr>
<td></td>
<td>Yes  No</td>
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<td></td>
<td>Yes  No</td>
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<td></td>
<td>Yes  No</td>
</tr>
<tr>
<td></td>
<td>Yes  No</td>
</tr>
</tbody>
</table>

2. The strength of the existing TDS:

High: The appropriate TDS exists and has functioned well in providing similar technologies. □

Medium: All components exist, but linkages between components are weak: (Specify which linkages are weak and how.) □

Low: One or more of the components necessary for an appropriate TDS do not presently exist. (Specify which) □
3. At the outset of this demonstration, did the federal agency have an explicit model of how the results of the demonstration would be used, and in particular how the diffusion process was to work?

(Circle one) Yes No No data

If so, please explain briefly what it was.

_________________________________________________________________
_________________________________________________________________
_________________________________________________________________
_________________________________________________________________
_________________________________________________________________
_________________________________________________________________
VI. PRE-PROJECT ACTIVITIES OF THE FEDERAL AGENCY

Our Phase I case studies suggest that federal agencies which undertake feasibility analyses, consult experts, and the like, are much more likely to select successful demonstration projects. The following questions relate to any filtering activities the federal agency might have taken before the final decision to go ahead with this demonstration project was made.

A. Was a feasibility study of the technology performed? □ □ □
   1. If so, by whom? ___________________________
   2. What was the nature of the findings? ______

B. Was an engineering report conducted? □ □ □
   1. If so, by whom? ___________________________
   2. What was the nature of the findings? ______

C. Was a market study conducted? □ □ □
   1. If so, by whom? ___________________________
   2. What was the nature of the findings? ______

D. Did the federal agency consult with independent experts about the feasibility of the demonstration proposal? □ □ □
   1. If so, with respect to what aspects of the project? ___________________________
   2. Who was consulted? ___________________________
   3. What was the nature of the responses from experts? ___________________________
E. In selecting this project for demonstration, did the federal agency employ any sort of evaluation framework?  

Yes No Data

If so, please describe, and provide copy if available.

F. Did the federal agency specifically address the following questions before funding this demonstration?  

Yes No Data

1. What the private sector was or was not doing to promote this technology?  

If so, explain.

2. What the rationale for federal intervention was into the development and diffusion of this technology, and in particular what the rationale for demonstrating the technology was?  

If so, explain.

G. Did the federal agency make any attempt to assess the importance of any institutional or organizational barriers (e.g., restrictive labor practices, sensitivity of demand to capital markets, etc.) to the diffusion of the results of the demonstration and/or to the process of the demonstration project itself?  

(Circle one) Yes No Data

Such concerns not relevant

1. If answer above is yes and significant barriers were judged to exist, did the federal agency take any steps to solve the problems caused by these barriers or during the demonstration?  

Yes No No data

2. If yes, explain steps taken and outcomes.
H. Did the federal agency identify specific target audiences for the demonstration?  
(Circle one) Yes No No data

Specify.__________________________________________________________

__________________________________________________________

__________________________________________________________

__________________________________________________________

I. Did the federal agency explore the possibilities for cost sharing with potential participants in the period before a contractor was selected?  
(Circle one) Yes No No data  
If "yes" please give brief description of steps taken.____________________

__________________________________________________________

__________________________________________________________

__________________________________________________________

__________________________________________________________
VII. PLANNING AND IMPLEMENTATION

A. Who conducted the concrete planning for this demonstration, i.e., made the detailed decisions about such things as size, design, timing, etc.? (We are looking for primary responsibility.)

1. The operating organization(s) □
2. The federal agency □
3. Shared between federal agency and operators □
4. Other (explain) □

If the concrete planners were not the operators, did any difficulties arise over the decision-making process?

(Circle one) Yes □ No □ No data □

If yes, please explain. ________________________________________________________________
________________________________________________________________________________
________________________________________________________________________________
________________________________________________________________________________
________________________________________________________________________________

B. Site Selection. We need to know whether the site selected for the demonstration was appropriate in terms of the goals of the demonstration, and the basis upon which the site was in fact selected.

1. The appropriateness of a given site is based upon a judgment of the extent to which the relevant characteristics of the site are representative of the problems and opportunities which will confront the adoption of the innovation generally. The relevance of site characteristics varies from demonstration to demonstration. The questions below elicit the extent to which the site was important and appropriate in the various uncertainty dimensions. These criteria are relevant for both information producing and exemplary type demonstrations.
<table>
<thead>
<tr>
<th>Site Selection</th>
<th>Not Important</th>
<th>Chosen Site</th>
<th>Chosen Site</th>
<th>No Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Important</td>
<td></td>
<td>Appropriate</td>
<td>Inappropriate</td>
<td></td>
</tr>
</tbody>
</table>

2. Did the selection of the site for this project create any difficulties for the demonstration?

(Circle one) Yes No No data

If so, were these difficulties specific to the chosen site, or could they be expected to arise generally?

General Site Specific Cannot Determine

3. On what basis was the site chosen? (Circle appropriate letters)

a. Local proposal determined site
b. Cost sharing opportunities were good at chosen site
c. Political pressure or political considerations appeared relevant to siting (explain, document if possible)

d. Site was chosen explicitly because it was deemed to be representative
e. No data
f. Other reasons (explain)

Which of the above do you judge to have been the most important in site selection? (Circle one)

a b c d e f
C. Size of the Demonstration. Under our definition, demonstrations can be of either "commercial size" or "semi-works size." A commercial size demonstration is one in which the technological system is as large as would be needed for an economically attractive commercial operation. A commercial size demonstration does not necessarily include as much redundancy or instrumentation etc. as would be present in an actual commercial venture. A semi-works demonstration typically uses less than commercial size equipment or demonstrates only a part of the total technological system that would be present in a commercial venture.

1. This demonstration was: (Circle one)
   
   Commercial Size       Semi-works Size       Unable to determine
   (explain)

2. Why was this demonstration conducted at this scale? (Brief explanation)

D. Cost and Risk Sharing. Cost sharing is essentially a contractual arrangement by which some organization other than the federal agency will pay part of the project's costs. For our purposes, it is risk sharing which is important. Risk sharing occurs when a successful project outcome is a condition for the cost sharing organization's recovering their investment.

1. Did this project involve cost-sharing? NOTE: revenues obtained from user fees or other charges is only to be considered cost-sharing where the users have agreed to pay more than a market price for the output in order to subsidize the demonstration project.

   Yes       No

[If the answer was no, go on to Section VII-E.]
2. Federal funding: $ %
   Non-federal cost sharing: $ %
   (If more than one, give separately)
   Other (e.g., user charges): $ %

3. If the project had failed to meet its basic objectives, would the local cost sharing organizations have suffered any loss, i.e., was there risk sharing? (Circle one)
   Yes          No          No data

4. What participants were risk sharers?

5. Was one of the cost-sharers an organization which could be expected to be instrumental in the diffusion of the technology if it were successfully demonstrated?
   Yes          No

E. Demonstration vs. Experimentation. Most demonstration projects will contain some experimental aspects which do not concern us here. We are concerned with cases which involved fairly extensive experimentation, i.e., cases in which the technological system was made operational, and then rearranged or redesigned, and then tested again in order to obtain incremental improvements in performance. (Cases in which the system was made operational but performed poorly which necessitated redesign are not to be considered experimental.)

1. Did this demonstration project involve substantial experimentation with the same facility? (Circle one)
   Yes          No          No data
   [If no, go on to Section VII-F.]

2. In what order was the experimental and demonstration activity performed? (Circle one)
   a. Experimentation first, demonstration later
   b. Demonstration first, experimentation later
   c. Mixed

3. Did using the facility for both purposes create any difficulties?
   Yes          No          No data
   If yes, please explain.
F. Cost/Performance/Time Tradeoffs. Our hypothesis that the time schedule for successful demonstration projects is made according to the difficulties inherent in planning and implementing this particular technology, and that any attempt to compress the time schedule risks lowering the performance of the project and increasing the costs.

1. On what basis was the time schedule for the demonstration made? (It is recognized that for some projects this may be very difficult to ascertain. If you cannot easily determine this, so state.)

2. Do there appear to have been any external time pressures on the completion of this demonstration? (By external we mean by any sources other than the parties to the demonstration. Included as external would be members of the federal agency outside the particular office funding the demonstration.)

   Yes  No  No data

3. If yes, what were the sources of time pressure?

4. Were you able to discern any difficulties in the demonstration process which arose from the schedule, whether or not external time pressures were present?

   Yes  No  No data

   If yes, explain.

5. Did this project overrun its budget?

   Yes  No  No data

   If yes, by how much? $_________

   To what do you attribute the overrun? ________________________________
VIII. MANAGEMENT, MONITORING, AND EVALUATION

A. One of the tentative conclusions which evolved from the Phase I case studies is that the performance of management tasks for a demonstration appear not to have much impact on project outcomes.

Does good or bad management (e.g., coordination, staffing, task assignment etc.) appear to have affected the results of this demonstration?

Yes  No  No data

If yes, please explain

B. Monitoring is the process by which the federal agency keeps abreast of the demonstration's progress. Monitoring practices of federal agencies vary from extremely "loose," e.g., introducing the project officer to the operating agency and little more, to fairly "tight," e.g., on-site project officers continually reviewing the decisions of the operators.

1. How would you characterize the monitoring of this demonstration?

   Loose  Moderate  Tight  Cannot determine  No data

2. Explain briefly the basis upon which this judgment is based.

   ___________________________________________________
   ___________________________________________________
   ___________________________________________________
   ___________________________________________________

3. Did the federal agency participate in the making of management decisions for this demonstration?

   Frequently  Sometimes  Rarely or Never  No data

4. Were disagreements on substantive points reported between the federal agency and the operators?

   a. Numerous major minor
   b. One or several major minor
   c. None
   d. No data
5. We are interested in knowing the kinds of monitoring devices used by federal agencies, and in particular those which do not involve direct federal supervision of the demonstration's activities. One such device is what we call "targeted evaluations," i.e., narrowly focused evaluations of some aspect of a demonstration project conducted during the course of the demonstration.

We targeted evaluations performed for this demonstration?

Yes No

If no, go to #6; if yes answer following for each targeted evaluation:

a. On what aspect of the demonstration?

b. By whom was it performed?

c. When in the demonstration was it performed?

d. What prompted the evaluation?

e. Who contracted for the targeted evaluation?

f. What use was made of the results?

6. Were surveys of user reaction to the demonstration performed?

Yes No Not appropriate to this case

If yes, describe briefly.

7. Was any other device used by the federal agency to obtain information about the operation of the demonstration?

Yes No No data

If yes, explain briefly.
C. Were other evaluations (e.g., ex-post evaluations) of this demonstration made?

Yes  No  No data

If yes, for each evaluation:

a. What was evaluated?

b. By whom was it conducted?

c. When?

d. What prompted the evaluation?

e. What use was made of the results?
IX. DISSEMINATION OF THE RESULTS

A. Does it appear that the results of this demonstration were accurately communicated to target audiences?

Yes  No  Unable to determine

Explain the basis upon which the above judgment was made.

_________________________________________________________________
_________________________________________________________________
_________________________________________________________________
_________________________________________________________________
_________________________________________________________________
_________________________________________________________________

B. What was the federal role in the dissemination process?

1. Reliance on private sector for dissemination; federal activities largely confined to general broadcasting (defined below) of the results. □

2. Federal agency actively disseminated demonstration results. □

3. Federal agency aided in the creation or change of the TDS for the innovation, and the results were disseminated in this process. □

4. Federal agency was or became a continuing part of the TDS for the innovation and disseminated the results through this activity. □

5. Other role; explain.

_________________________________________________________________
_________________________________________________________________
_________________________________________________________________
_________________________________________________________________
_________________________________________________________________

If more than one box is checked, please explain.

_________________________________________________________________
_________________________________________________________________
C. Dissemination devices used by the federal agency. Check the appropriate box if the device was employed by the federal agency to promote dissemination.

<table>
<thead>
<tr>
<th>Device and Definition</th>
<th>Was Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. National conferences of potential adopters and/or manufacturers.</td>
<td>☐</td>
</tr>
<tr>
<td>2. Local conferences: a series of conferences held in local areas</td>
<td>☐</td>
</tr>
<tr>
<td>defined by similar problems in adopting the technology;</td>
<td></td>
</tr>
<tr>
<td>conferences tailored to local concerns.</td>
<td></td>
</tr>
<tr>
<td>3. General broadcasting consists of such things as press releases,</td>
<td>☐</td>
</tr>
<tr>
<td>journal articles, newspaper articles, and the like.</td>
<td></td>
</tr>
<tr>
<td>4. Targeted broadcasting consists of the preparation of pamphlets,</td>
<td>☐</td>
</tr>
<tr>
<td>reports and the like which are specifically designed to meet the needs and questions</td>
<td></td>
</tr>
<tr>
<td>of particular audiences.</td>
<td></td>
</tr>
<tr>
<td>5. Face-to-face contacts. Did the federal agency make an effort</td>
<td>☐</td>
</tr>
<tr>
<td>to encourage personal contacts between those involved with the</td>
<td></td>
</tr>
<tr>
<td>demonstration and target audiences to aid dissemination?</td>
<td></td>
</tr>
<tr>
<td>6. People transfer consists of transfer of personnel who were</td>
<td>☐</td>
</tr>
<tr>
<td>involved in the demonstration project to potential adopters or</td>
<td></td>
</tr>
<tr>
<td>manufacturers of the innovation.</td>
<td></td>
</tr>
<tr>
<td>7. Site visits were encouraged</td>
<td>☐</td>
</tr>
<tr>
<td>8. Other; explain.</td>
<td></td>
</tr>
</tbody>
</table>

D. Did any of the devices used appear particularly effective?

Yes  No  No data

If yes, please explain.  

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________
X. OUTCOMES

The following questions elicit the results of the demonstration project in the various dimensions of success and failure. To a certain extent the process of assigning outcomes is necessarily judgmental. It is very important, however, that we make these judgments on a common basis. Therefore careful attention to the definitions is essential.

Information success occurs when a demonstration project reduces uncertainties (in the five dimensions below) to a point where potential adopters can make informed decisions about whether they wish to adopt the technological innovation. Information success is dichotomous. For a project to be judged an information success does not require that uncertainty to eliminated in all five dimensions, but it does mean that whatever uncertainty remains which would bar the making of an adoption decision could not have been resolved by the demonstration project. For example, after a demonstration project which was an information success, there might still remain so much uncertainty about the availability of requisite inputs that the technology will not diffuse. Such uncertainty might be reduced by paper studies, or even prove intractable, but the demonstration would still be an information success. A project is an information success whenever uncertainty in all five dimensions has been reduced to "low" by the definitions that follow, provided that the project did not start with "low" uncertainty in all dimensions (i.e., an exemplary demonstration).

<table>
<thead>
<tr>
<th>High uncertainty:</th>
<th>Uncertainty is &quot;high&quot; in a dimension when there are major unknowns. For the technology this usually indicates that more research and development is in order. For demand the basic market parameters will be unknown; for the cost dimension, high uncertainty means that cost estimates will vary greatly.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(hi)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Medium uncertainty:</th>
<th>Uncertainty is &quot;medium&quot; in a dimension when the strategy for how the uncertainty can be reduced is clear. Medium uncertainty can be reduced by a demonstration project or perhaps by other means, but not by paper studies.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low uncertainty:</th>
<th>Uncertainty is said to be &quot;low&quot; in a dimension when either there exist no substantial questions about the applicability of the innovation in that dimension, or what uncertainty does exist relates to local factors and can be reduced by means of paper studies.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(lo)</td>
<td></td>
</tr>
</tbody>
</table>
In those cases which appear borderline between two levels, the levels may be combined, e.g., medium-low. This should only be done where necessary.

A. For this demonstration project, fill in the appropriate spaces for the five uncertainty dimensions with 'Hi', 'M', 'Lo'.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Pre-Project</th>
<th>Post-Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Institutional/Organizational</td>
<td></td>
<td></td>
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<tr>
<td>Externalities</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B. Was this project an information success? Yes ☐ No ☐

C. In those cases in which the resultant product or service of the innovation substitutes for an existing product or service, a good measure of information success is what is learned about the relative cost advantage of the innovation.

Did this demonstration show that the technology demonstrated was:

1. Cost advantageous ☐
2. Cost disadvantageous ☐
3. Did not demonstrate either (remains uncertain) ☐
4. No data ☐

D. Application success is a measure of how well the demonstrated technology met the local needs at the site. Application success need not be accompanied by either information success or diffusion success.

Application success is "high" where the demonstration project provided the product or service to its local users on a reliable basis after operations began.

Application success is "medium" where the product or service was provided but with some minor problems with respect to such things as reliability or quality.
Application success is "low" where the project either failed to provide the product or service or where serious problems of reliability and/or quality arose, or where the product or service was so unexpectedly costly that users refused the output.

Application success for this project was:

1. High
2. Medium
3. Low
4. No data
5. Not applicable (explain)

E. Diffusion success is a measure of the extent to which the technology demonstrated has passed into use. Given our inability to secure baseline data on typical diffusion trends and the variability in time expired from the demonstration projects' termination, our determinations of diffusion success are less precise than we would like.

Following are the definitions for a possible diffusion scale.

Significant diffusion is said to have taken place when the process of adoption of the technology* subsequent to the demonstration is proceeding within the private sector without federal intervention on a case-by-case basis,** i.e., the diffusion of the technology is self-sustaining.

Some diffusion is said to have taken place when the technology has been adopted in one or more non-demonstration applications but diffusion does not appear to be self-sustaining without further government intervention. In such cases the diffusion of the technology is problematic.

* Counted as an adoption would be systems which are largely based upon the demonstrated technology but with local adaptations, improvements, and changes of scale as well as essentially carbon copies of the demonstrated system.

** Intervention on a case-by-case basis means that the government is instrumental in pushing the particular adoption in a particular place, and is not meant to include cases in which the government has established a general subsidy or other aid program which benefits the adoption of the technology, e.g., the Price-Anderson Act for nuclear reactors.
No diffusion is self-explanatory.

1. On the basis of the above definitions, the diffusion of the technology has been:
   a. Significant  
   b. Some  
   c. None  
   d. No data  
   e. Other, explain. 

2. How many adoptions of the innovation have taken place? 

3. (If readily available) what percentage of the total market does this represent? 

4. How many adoptions are in the active planning stages? 

5. How many feasibility studies for the adoption of the technology have been or are being conducted? 

6. If the time since the completion of the demonstration is one year or less and diffusion has not begun, what is your judgment about the prospects for the diffusion of the technology, and on what basis do you make this judgment? 

7. Has there been parallel development of this technology in the private sector, and if so, how much (if any) of the diffusion of the technology can you attribute to this private sector (or other non-demonstration specific) activity? 

8. Did this demonstration project appear to have speeded up the rate at which this technology would be diffused, and if so explain the basis upon which this judgment is based?
F. In the following pages, please trace what you consider to be the primary variables which explain the sets of outcomes delimited in this section.