"RAPID" INNOVATION AND INTEGRATION OF COMPONENTS: COMPARISON OF USER AND MANUFACTURER INNOVATIONS THROUGH A STUDY OF RESIDENTIAL CONSTRUCTION

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ABSTRACT

According to conventional wisdom, builders of residential housing almost never innovate. In a detailed field-based study of the residential construction industry, I document quite a different picture: builders, rather than the manufacturers of products and materials, are the developers of almost all of the innovations in a sample (n=34) researched in depth.

Through structured interviews with over 50 individuals in the industry, I collected specific data on a sample of 34 innovations relating to a single technology in residential construction, the stressed-skin panel. As background for this detailed analysis, I also collected a sample of 117 innovations that are permanently installed in a residential building.

Measurement and comparison of economic incentives operating on builders and manufacturers in this industry show how a pattern of builder innovation can make economic sense. Builders develop needs for innovations in the middle of construction work, and at that time the cost of delay is very high. They must also integrate varied components into a whole operational residential structure. Under these conditions builders find innovation to be cost-effective; as a result, they rapidly innovate. The prevalence of these innovations indicates a de facto design partnership between these builder-users and manufacturers.

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This thesis is dedicated to my husband, Jim Newman, whose expertise and emotional support over these years made it all possible. It's also dedicated to our son, Gage.

> Three things are to be looked to in a building: that it stands on the right spot; that it be securely founded; that it be successfully executed.
>
> Johann Wolfgang von Goethe

> For three things...ought to be considered in every fabric, without which no edifice will deserve to be commended; and these are utility or convenience, duration and beauty...Beauty will result from the form and correspondance of the whole, with respect to the several parts, of the parts with regard to each other, and of these again to the whole.
>
> Andrea Palladio
> The First Book of Architecture

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CHAPTER 1: INTRODUCTION

1.0 Introduction

The purpose of this research is to expand our theoretical and empirical understanding of "learning by doing" (Arrow, 1974) and "learning by using" (Rosenberg, 1982) in the innovation process. I examine innovation during the implementation stage of a technology by drawing from a detailed, comprehensive, field-based study of innovations in stressed-skin panels in the residential construction industry, in the tradition of Glasser and Strauss (1967), Strauss (1987), and Eisenhardt (1989).

There are many ways of examining this problem; the one that provides the most insights is the model of "user innovation". As von Hippel has shown convincingly, user innovation is of great importance in a wide variety of industries (von Hippel, 1988). However, existing research on this topic has focused almost exclusively on the subset of user innovations that are commercialized by manufacturers; the attributes and importance of user innovations that are not commercialized remain to be explored, and therefore our understanding of the full scope of innovation by users remains limited as well (Cainarca et al., 1989; Rogers, 1983). An objective of this research is to respond to this deficiency by identifying a full set of manufacturer and user innovations associated with a single technology, and by distinguishing among the operative incentives and mechanisms for appropriating the benefits associated with the innovations.

Several preliminary studies and some anecdotal evidence imply that technological change often occurs during the application of a technology (Bell and Hill, 1978; Tietel, 1984; Rogers, 1983). In many cases, the problems that provoke these changes are expected by the people who employ the technologies, but the exact nature of these problems are only identifiable during actual use. While the original providers of the technology may be aware that needs arise during application, the recipients of the technology may be in a better position to both identify the exact nature of the needs, and to meet them through their own innovations.

Users create most of the innovations in this study; through detailed evidence, I show that the reasons for this are much more complex than previously understood. A key implication of this research is that in industries characterized by highly sophisticated users and by technologies that must be integrated "in real time", users are likely to be a rich source of innovations essential in connecting separate technologies into a whole operating unit.

1.1 Related Literature

Traditional models of innovation assume that technological innovation originates either from the manufacturers or from research and development laboratories. Many models concentrate on the response of manufacturers to market demands through technological innovations (Myers and Marquis, 1969; Abernathy and Utterback, 1978; Mansfield, 1968; Kamien and Schwartz, 1975; Nasbeth and Ray, 1974; Rogers, 1969; Vernon, 1971). Other research on innovation analyzes the contribution of research and development conducted by government or university laboratories to the public good (Fusfeld, 1986: Brooks, 1981; Isenson, 1969; Jervis, 1978). These models fail, however, to consider alternative sources of innovation, or the actual stages of implementation of the new technologies after they are introduced.

As mentioned earlier, the model which provides the most insight into this problem is that of "user" innovation. As von Hippel (1988) has shown conclusively, "users" of innovations as well as manufacturers can be sources of innovation and can contribute significant product and process developments. His research examined specific technological developments within nine different industries and found that users innovated in <u>all</u> nine industries and were <u>major</u> sources of the technological innovations in over half of these industries. From this research, von Hippel concluded that the source of innovation can be predicted by which participant expects to appropriate the economic benefits from the innovation. The costs of innovating for comparable products were analyzed, and it appears that users innovate when the technology is easy to modify, specifically when the costs for the user to innovate are decreased (von Hippel and Finkelstein, 1979).

Other research builds upon von Hippel's work. Several studies have found that the degree of innovation by users does not depend upon their expertise in the particular field (Voss, 1985; Feld, 1990). The manufacturers were seen to increase the rate of user innovation through lowering associated costs and increasing the ease of accomplishing the changes; these user innovations could then effectively be incorporated by the manufacturers into future product developments (Feld, 1990; Habermeier, 1990). Finally, when given the opportunity, users continually innovated and constantly exchanged information about those innovations (Johnson and Brown, 1986; Leonard-Barton and Rogers, 1981).

These findings have been echoed in work by other scholars in different fields. "Re-invention" or the alteration of the technology by users was often identified during the adoption and implementation stages to fit local conditions (Rogers, 1983; Bell and Hill, 1978; Teitel, 1984). Indeed, when the choice of the technology and other activities by the recipient of technology transfer is explicitly considered, modifications by users were often essential in achieving a successful transfer (Teitel, 1984; Bradbury et al, 1978). These modifications can be seen as economically rational responses to existing conditions, such as market demand and uncertainty. While these studies expand our understanding of the frequency of innovation by the users, they often fail to examine aspects of the technology itself in providing incentives and opportunites for innovation.

New research reveals that users may "retrofit" a technology when multiple generations of a technology coexist and "the system integrator function is carried out directly by the user" (Cainarca et al., 1989). Cainarca and colleagues found that the "users want solutions consistent with their knowledge base and organization, while suppliers lack user-specific information and might not generalize specific needs." In consequence, users generate their own solutions to bridge the gap between the promise of the new technology and the known operational characteristics of the old technology.

The constraints of these studies are related to the traditional models in innovation upon which they build, namely the focus on the manufacturers and the benefits they can appropriate from innovations. This approach perpetuates the view that user innovation may represent a "partly pathological response to market disequilibria" (Cainarca et al, 1989), that is, a failure on the part of manufacturers to meet existing market needs.

1.2 Contribution of the Thesis to the Existing Literature

This brief survey of the relevant literature indicates the complexity and importance of the issue of innovation during implementation. Further analysis of this topic must include explicit consideration of existing incentives for innovation by users and manufacturers during this stage. There remains much we do not know about user innovations, such as "how often do users innovate?" "Do user innovations differ quantitatively or qualitatively from manufacturer innovations?" "Are only certain types of user innovations commercialized by manufacturers?" This research attempts to answer these questions through a detailed field study of innovations relating to a specific technology that appear during use.

Existing studies of this issue do not comprehensively examine this category of innovations. The primary contribution of this research is a systematic examination of what actually occurs during implementation. This research uses detailed technical, managerial and economic information to examine how problems that occur during application are solved by users through learning by doing. It is a first step at expanding our understanding of the relative contributions of user and manufacturer innovations to meet market demands.

This research also attempts to integrate many of the existing theories of innovation, technology transfer, and diffusion. Using the insights available from these fields, this research is based upon the concept that the progression of a technology from original development to final use is a continuous process of innovation, with inherent cooperation between users and manufacturers to achieve a successful application. It theoretically and empirically explores innovation after diffusion or technology transfer. Specifically, it analyzes the benefits available to users and manufacturers from innovating, and the mechanisms they can use to collect those benefits. It also evaluates the value of these innovations with respect to the integration of disparate components into a functional whole unit. These issues are key to our comprehension of the continuum of the innovation process.

Finally, this research contributes an analysis of the construction industry. This industry is rarely studied for issues pertaining to innovation, since it is often assumed that little innovation occurs in the construction industry in general, and the residential building segment in particular. This research demonstrates that even in this "worst case", innovation consistently occurs, and the builder-users have previously unrecognized capabilities that equip them to respond to complex application requirements by creatively solving the problems they identify. This research can thus not only add to our general understanding of innovation during implementation, but may also improve the management of innovation in construction itself.

The multi-disciplinary approach used in this research provides insights into this complex and important issue. While this is an ambitious undertaking, this research can be a first step in expanding our understanding of innovation in general, and particularly its occurence during use through learning by doing.

CHAPTER 2: THE RESIDENTIAL CONSTRUCTION INDUSTRY

2.0 Introduction

My empirical research is based upon a detailed field study of the residential construction industry, and focuses on a single major innovation in the construction of dwellings: the stressed-skin panel. The purpose of this chapter is to set the context for this research by providing background information on the residential construction industry. In the first section, I outline the common assumptions about innovation in residential construction. The second section briefly describes the structure of the industry, particularly those aspects that pertain to the development and use of innovations.

2.1 Innovation in the U.S. Residential Construction Industry

Conventional wisdom assumes that innovation does not occur in residential construction. While other industries seemed to advance in great strides in manufacturing techniques during the 20th century, construction had a reputation of remaining at a standstill. In 1947, Fortune magazine dubbed residential construction as "the industry capitalism forgot", charging that the Industrial Revolution had left the industry behind because of its "feudal controls and chronic incompetence" (Fortune, 1947, quoted in Dowall and Lynch, 1986). Another study concluded that for the first half of the 20th century, no technical changes of major economic significance had occurred in building construction (Arthur D. Little, Inc., 1963). One analysis stated that "of all the commodities that have been touched by the industrial revolution, the house has remained almost impervious to change" (Burns and Mittelbach, 1968).

Homebuilding has been consistently characterized as "suicidal, a headless monster, and an army of pygmies" (Ventre, 1979). Even recent studies have deemed residential construction a "backward industry", concluding that "construction remains craft-based and labor-intensive, with vast scope for productivity improvement through better technologies" (U.S. Congress Office of Technology Assessment, 1987).

Not all studies, however, have concluded that innovation does not occur in residential construction. One study listed 86 selected product innovations and 19 method innovations, and asserted that the industry is "not one of the most technologically backward in the U.S." (emphasis in the original), but also predicted that future innovations would not be radically different from existing technologies (Johnson, 1968). A second study found evidence that productivity in construction significantly increased from 1947 to 1968, primarily due to technological innovation (Sims, 1968). More recent studies have confirmed the existence of innovation in construction; one study concluded that construction is being "radically re-shaped by new technologies," such as computers, modular components, and materials (U.S. Congress, Office of Technology Assessment, 1986a). Another cited innovations in residential construction in management and the use of robotics (Tatum, 1986).

Some studies have examined not only the development but also the use of innovations in residential construction; one study that represents the usual approach to this issue supposed that "if most potential innovations are evolutionary and reduce costs for a small component of the building production process, this suggests that the rate of adoption by builders will be low" (Quigley, 1982). Yet a study that specifically analyzed the diffusion rates of 14 innovations in residential construction (each of which an incremental and inexpensive advance) found that they were diffused in the same way and at the same speed as comparable innovations in other industries (Ventre, 1973; Ventre, 1979). A later study further analyzed this phenomenon, and found that innovations were most widely used when they had even an incremental cost savings, and, more importantly, when they did not decrease the value or performance of the completed dwellings (Duke, 1989).

Most of the improvements acknowledged in the construction process and finished dwellings are attributed to government research laboratories or to manufacturers, rather than to builders. These innovations are primarily in the areas of materials, tools, and factory assembly techniques (Quigley, 1982; U.S. Congress, Office of Technology Assessment, 1986b). Changes in on-site construction methods are not given great weight; the greater value is given by these studies to innovations which are widely commercialized by manufacturers (Special Advisory Committee, 1968; U.S. Congress, Office of Technology Assessment, 1987; U.S. Congress, Office of Technology Assessment, 1986b).

Government programs have used these findings that innovations originate from manufacturers and have based their policies to encourage innovation in residential construction upon the assumption that the best way to increase the rate of innovation was to involve manufacturers from other industries directly in the fabrication of houses. The objectives of this involvement were to speed the transfer of existing innovations into residential construction as well as to foster the development of new ones.

The two major government programs in homebuilding since WWII exemplify this trend and demonstrate the inherent difficulties of the assumption. They encouraged non-construction companies to enter the industry with new manufacturing techniques but without the knowledge, skills, and experience needed to make them work. In the first program, the federal government established a factory-production system in 1946 to pre-fabricate houses, but only 74,000 units were produced at a total cost of $200 million (U.S. Congress, Office of Technology Assessment, 1986b). Operation Breakthrough, the second program, subsidized major industrial companies who had no previous experience in the construction industry (such as General Electric, Republic Steel, American Cynamid, Phillip Morris, AlCan, and Warner Communications) to design and build prototype houses incorporating their own innovations. By 1972, only 26,500 were built, of which only six percent were ever offered in the competitive market. The total cost to the government was over $72 million. None of the Operation Breakthrough participants continued as functioning members of the residential construction industry (Quigley, 1982; Nelkin, 1971; U.S. Congress, Office of Technology Assessment, 1986b).

These two major programs to improve the innovative capacity of residential construction by importing manufacturing techniques from other industries assumed that major re-adjustments would not be required in either the construction process or in the housing market itself. The structure of the programs excluded the traditional trades and crafts associated with residential construction, thereby losing the accumulated knowledge and experience from these skill groups.

While some research has identified the contribution of manufacturers, little information has been gathered concerning innovation with respect to on-site construction processes. Most research on innovation in residential construction to date has focused primarily on innovations which are commercially available from manufacturers. A great number of studies used only aggregate statistics and other general measures. Yet many of the studies noted the lack of information about innovations influencing the actual construction methods for residential dwellings (Strassman, 1978; Chang et al, 1988; Ehrankrantz Group, 1979; U.S. Congress, Office of Technology Assessment, 1986a); this research is a response to that need. All innovations, both those of the manufacturers and those generated by the builders themselves, need to be considered in depth, particularly those which have not been commercialized by manufacturers and are not available in the general market. In such a strongly craft-based industry, a significant portion of the innovations may be new methods and techniques rather than new products.

I propose that the full extent of innovative activity in the residential construction industry is under-represented by concentrating on manufacturer products alone. From analysis of my samples of residential construction innovations, I conclude that, contrary to current assumptions, a newly constructed residential dwelling is very different from one constructed even fifty years ago, not only in terms of the building components used but also in the techniques and methods employed and the overall performance of the completed structure. (Please refer to Chapter 4 for more information about samples and data collection methodology. The innovations are described in Appendices A and B.)

Even a cursory examination of the sample of permanently-installed innovations (Appendix B) reveals that innovation occurs in residential construction to an extent not previously documented. This sample contains over 110 innovations that exist in a finished dwelling, from the foundation to the roof, but it represents only a portion of all innovations which have appeared in residential construction. For this sample, almost 20 percent of the innovations are <u>not</u> commercially supplied by any manufacturers; I would suggest that if it were possible to identify all of the method innovations currently used in constructing a house, the observed incidence of innovation might increase significantly. For instance, many of the new products commercialized by the manufacturers require complementary innovations to make them work on the site. These may involve significant changes in current practice, and add great value to the finished structure, as will be explored in greater detail in later chapters about innovations relating to stressed-skin panels. Further analysis can explore the nature of all innovations in residential construction, particularly the benefits which they can offer despite the considerable barriers to innovation in this industry.

2.2 Structure of the Residential Construction Industry

Several characteristics of residential construction affect the development and use of innovations in this industry. The market itself is very large but unstable and highly fragmented, thereby creating an uncertain climate for investment in innovation. Residential builders are often very small companies that lack the resources to either develop innovations or search extensively for them. A few large manufacturers dominate most of the construction supply markets and so perceive little need to innovate consistently. The need to meet specific project requirements, however, can provide adequate incentives for innovation.

2.2.1 The Residential Construction Market

The construction industry is an important segment of the U.S. economy. In 1985, new construction expenditures totalled over $342 billion, equalling 9 percent of the U.S. Gross National Product (U.S. Congress, Office of Technology Assessment, 1987). Constructed facilities constitute 55-65%

of total capital investment in the U.S. (Moavenzedah, 1985). Employment in the industry, which equals over 5 million people or 10 percent of the employed labor force, has increased by over 30% in the last decade (Predicasts, 1988). If other related industries, such as engineering, architectural services, and financial institutions, are included in the calculation, construction can be seen to employ 15 percent of the total U.S. employed labor force (Ventre, 1979).

Residential construction is the largest portion of the U.S. construction industry, commanding virtually one half of all new construction expenditures (Table 2.1).

Table 2.1: New Construction Expenditures in the U.S. by Construction Market, 1987

MARKET	$ MILLIONS	PERCENT
Residential	$196,291	49%
Office, commercial	62,825	16
Industrial and public utilities	47,744	12
Highways, water, sewer	35,194	9
Other public	25,815	6
Institutional	23,271	6
Other private	7,710	2
TOTAL:	$398,850	100%

SOURCE: Standard & Poor's, 1988.

Residential construction expenditures include not only new construction but also renovation and rehabilitation, which equal a third of the annual total (Table 2.2). Total residential construction expenditures in 1988 equalled over $300 billion (U.S. Department of Commerce, 1990).

Table 2.2: Total Residential Construction Expenditures in the U.S. by Type of Expenditure, 1988

TYPE OF EXPENDITURE	$ MILLION	PERCENT
New Construction*	$200,000	66%
Additions, alterations	43,449	14%
Maintenance, repair	40,885	14%
Major replacements	16,893	6%
TOTAL:	$301,227	100%

*Based on estimated increase from 1987 new construction expenditures.

SOURCE: U.S. Department of Commerce, March-April 1990.

Although the residential construction market is a large and important part of the U.S. economy, it also has several distinct characteristics which present problems with regard to the development and use of innovations. The market is extremely cyclical and sensitive to seasonal variations, with expenditures decreasing not only during the winter months, but also with slowdowns in the local or national economies (U.S. Department of Commerce; Bureau of the Census; Tatum, 1986; U.S. Congress, Office of

Technology Assessment, 1986b). These market variations can significantly decrease incentives to invest capital for technological development, as well as for the training required to utilize new technologies efficiently (Manski, 1973).

Over 1 million new housing units were constructed in the U.S. during 1989, which is a decrease from the peak production in 1986 of 1.8 million homes (Table 2.3). The majority of residential structures are single family homes, equalling 70 percent of the total constructed in 1989; this percentage has increased in recent years, in part because of the recent tax law changes that reduced tax benefits from rental units. These statistics on new housing starts demonstrate the volatility of the housing market, not only in the number of new units, but also their distribution among different sized structures.

Table 2.3: New Privately Owned Housing Units by Number of Units in Structure, 1985 to 1989

Year	Total (000s)	Portion by Number of Units 1	2	3-4	5+	(Total)
1985	1,733.3	55%	3%	4%	38%	(100%)
1986	1,769.4	61	3	3	33	(100)
1987	1,534.8	67	3	3	27	(100)
1988	1,455.6	68	2	3	26	(100)
1989	1,340.6	70	2	3	25	(100)

Source: U.S. Department of Commerce, Bureau of the Census, February 1990.

The market for housing is also strongly segmented into localized regions, which severely fragments demand for the builders. This fragmentation discourages innovation by constraining the potential benefits a builder could obtain to a limited number of construction projects within the local area. Unlike the products of most other major industries, the end product of residential construction is permanently installed on a specific site and so the demand for dwellings is defined by its locality. For example, a house constructed in Dallas is not interchangeable with one constructed in New York, in terms of who will buy it or who will live in it.

The demand for new housing varies greatly among regions. As the local economy grows, the population increases and the demand for housing increases. In the U.S., the region with the largest growth in demand for new housing is the South, which currently accounts for approximately 40% of all new residential units built in the last five years (Table 2.4).

Table 2.4: New Privately Owned Housing Units by Region, 1985 to 1989

Year	Total (000s)	Proportion by Region			
		South	West	Midwest	Northeast
1985	1,733.3	43%	28%	14%	15%
1986	1,769.4	39	29	16	16
1987	1,534.8	37	26	18	18
1988	1,455.6	37	29	18	16
1989	1,340.6	38	30	19	13

Source: U.S. Department of Commerce, Bureau of the Census, February 1990.

A final major market factor affecting innovation in residential construction is regulation through building codes, which are locally specified and enforced. These codes can effect not only the selection of the specific technologies but also how they are used. Four national building codes form the basis of the local ordinances. While they increasingly conform to a single national standard, the local enforcement of these codes can differ significantly among localities (Duke, 1988; Ehrenkrantz Group, 1979). Local and state building departments select a model code, and add or modify specific entries to fit local conditions and objectives (Bobenhauser, 1989; Carlson, 1989). Even though new editions of the model codes appear approximately every three years, with annual hearings on suggested changes, the modification of these codes to acknowledge a specific technology may take at least three years, and can easily take longer. The local code departments infrequently alter their regulations to accept specific innovations, usually well after acceptance in the model codes (Duke, 1988; Ventre, 1973; Ehrenkrantz Group, 1979).

Building codes contain three major types of information: definitions, licensing requirements, and standards. The definitions and licensing requirements describe each system and the trades which are allowed to install them, which can impede innovations that challenge current trade divisions. The standards are the areas with the greatest variation; they can be specific descriptions of acceptable techniques or general performance requirements. Performance-based codes, where a system is required to perform at a certain level after installation, can be especially difficult to enforce because the field inspectors rarely have the training or specific equipment to verify compliance. The inspectors therefore rely on their own experience and knowledge of standard techniques, which can alter the performance codes back to task and technique specification (Carlson, 1989; Bobenhauser, 1989; from field interviews).

The localized nature of the building codes can create an uneven environment for a builder. The codes may differ among neighboring towns on which innovations are acceptable, a conflict that can entail significant delays and costs for the builder. In addition, the local building departments may not have the information necessary to rule on the acceptability of certain innovations. To use an innovation, a builder may have to contend with complex, conditional, and extended application and appeal systems to obtain the necessary permission for any one town, and may have to repeat the process for additional jurisdictions.

The results of recent research on the effect of the building codes on building costs and the use of innovation are conflicting. Some studies conclude that building codes significantly increase housing costs and decrease the application of innovations (U.S. Housing and Urban Development, 1988a;

Quigley, 1982). Other studies assume that because the model codes are converging on a single national code, the local building codes will also become less variable, and soon will have no appreciable effect on either housing costs or the use of innovations (Ventre, 1973; Duke, 1988).

2.2.2 Segments of the Residential Construction Industry

Many different segments of the U.S. economy add value to a completed residential building. Two primary sectors, manufacturers of building components and residential contractors, are described in greater detail in the following sections. This section will provide a brief overview of the involvement of other professions in residential construction.

The costs associated with the construction of a new home can be broken down into specific categories (Table 2.5) for 1970 and 1980. One strong pattern is the higher proportional increases in the costs of land and financing compared to the cost for on-site labor; however, a discussion of the intricacies of the financial industry with respect to residential housing is beyond the scope of this research. Few analyses have fully examined the effect of this increase on the value of new homes, but one study noted that the conservatism of financial institutions discourages the use of new technologies (Ehrenkrantz Group, 1979).

Table 2.5: Approximate Costs for a New Single-Family Home by Category, 1970 and 1980

	1970		1980		1980 to 1970
Category	Cost	Percent	Cost	Percent	Increase
Financing	$1,600	7%	$7,700	12%	4.8
Land	4,450	19	15,500	24	3.5
Materials	8,650	37	22,000	34	2.5
On-site labor	4,500	19	10,350	16	2.3
Overhead /profit	4,200	18	9,050	14	2.1
Total:	23,400	(100%)	64,600	(100%)	2.8

Source: U.S. Congress, Office of Technology Assessment, 1986b.

From 1985 to 1990, the average cost of residential lots rose 62.5 percent in the U.S., though this increase varied widely among different regions. Some cities, such as Boston and San Jose, saw land costs rise over 100 percent, while other areas, such as Houston and New Orleans, saw little or no increase (Progressive Architecture, December 1990).

The land upon which a house is constructed must be prepared for a residential structure, such as the provision of supply sources for water, sewage, and electrical services. A "developer" purchases a tract of land, and installs access roads, drainage systems, and service lines, as well as laying the size and orientation of the individual lots. These developed tracts may be as small as only two lots or as large as several hundred lots. There are approximately 6,000 companies which operate primarily as developers in the U.S. (U.S. Department of Commerce, Bureau of the Census, 1989). Although some regions are increasing the requirements for land development, most price increases are attributable to a decreasing supply of open land coupled with an increasing demand for new housing (U.S. Department of Housing and Urban Development, 1988a).

A developer may also act as the general contractor to construct houses on the lots. For instance, Levitt and Sons often constructed over 1,000 units a year during the early 1950s on large tracts of land that they themselves developed (Eichler, 1982). One source estimates that 10 percent of all new single family homes built in 1990 were constructed by builders as "speculative" homes, that is, without a specific client at the beginning of the construction process (Custom Builder, November 1990).

Most residential buildings are completed without the involvement of architects. Although the code regulations vary by state, they usually do not require the seal of an architect or engineer (either one is acceptable) unless the structure is over 5,000 square feet (Schott, 1990). Since the average new home built in 1986 was only 1,825 square feet, and only one-third of all the homes were greater than 2,000 square feet, the number of residential structures that require architectural approval is small (Wright, 1990). In general, architects design residential buildings either for the custom market for higher income clients, or for public housing projects. "Designers" or "design/builders" can produce drawings upon which construction can proceed, often at a significantly lower price than an architect's fees (Schott, 1990).

The median sales price for a new home in 1989 was $120,000, up from $79,900 in 1984. These prices vary greatly by region; the Northeast saw the greatest median price increase over these five years, from $88,600 in 1984 to $159,000 in 1989, while the South has the lowest sales prices, at $72,000 in 1984 and $95,600 in 1989. Despite the high cost of purchasing a house, most people own their own homes; out of the over 88 million existing residential units in the U.S., over 60 percent are occupied by the owner (U.S. Department of Commerce, Bureau of the Census, 1985).

From developing the land to fabricating the components used to construct a home, many stages add value to the final dwelling. The following sections will examine the contribution of residential builders and component manufacturers in more detail.

2.2.3 Manufacturers of Construction Components

Manufacturers supply the residential construction industry with a wide variety of products, ranging from lumber and nails to plumbing fixtures to millwork. One source estimates that out of 819,000 site-built homes constructed in 1987, over 80 percent used some selection of pre-assembled building components, such as a window unit that includes a frame as well as the sashes (Red Book of Housing Manufacturers, 1987).

The cost of the components used in a residential building (which for this research includes processed materials such as lumber and plywood as well as the pre-assembled units) has steadily increased over the last few decades. Not only has the materials cost increased at a greater rate than the cost for on-site labor (Table 2.5), but it has also increased more than other commodities have (Table 2.6).

Table 2.6: Producer Price Indexes of Building Materials (1982=100)

Building Material	1987
Gypsum products	125.2
Structural clay products	121.4
Building block	120.2
Plumbing fixtures	119.7
Lumber	118.2
Millwork	117.7
Hardware	117.4
Heating equipment	115.5
Metal doors, sash, trim	112.0
Building paper and board	111.2
Concrete ingredients	110.4
Concrete products	109.4
Prepared paint	108.1
Plywood	102.6
Asphalt roofing	91.9
All construction materials	109.5
All commodities	102.8

Source: Standard & Poor's, 1988.

Most component markets for residential construction are dominated by a few large companies (Table 2.7). According to some theories, "when the leading four firms control 40 percent or more of the total market, it is fair to assume that oligopoly is beginning to rear its head" (Scherer, 1980). As can be seen from the table, over half of the listed product classes indicate significant market concentration, as measured by the share of the four largest firms.

Table 2.7: Market Concentrations of Selected Manufacturers for Construction-Related Markets, 1982

PRODUCT CLASS	4 LARGEST FIRMS' SHARE OF MARKET
Household refrigerators	94
Household laundry equipment	91
Flat glass	85
Gypsum products	76
Vitreous plumbing fixtures	63
Household cooking equipment	52
Structural clay products	46
Particleboard	43
Construction machinery	42
Woodworking machinery	41
Softwood plywood	41
Plumbing fittings	34
Products of purchased glass	30
Hardwood plywood	25
Paints and allied products	24
Brick,structural tile	24
Heating equipment (not electric)	15
Millwork	15
Concrete products	10
Concrete block	8

NOTE: The market share is calculated from the percent of value of shipments accounted for by the four largest firms.

SOURCE: U.S. Department of Commerce, Bureau of the Census, 1982.

The market concentration of the component manufacturers contrasts sharply with the market fragmentation of the builders; the builders can not exert market leverage on manufacturers to introduce innovations. Even for the most basic building components, such as gypsum products and plywood, a concentrated demand for a new product by the largest builders would still only constitute a small fraction of the manufacturers' total markets. The manufacturers therefore perceive little demand for new products.

Most manufacturers reach builders through distributors, such as lumber yards, hardware stores, or sales representatives. These distributors usually carry the products of only a few manufacturers, acting as their agent. While they can answer questions and provide solutions to problems concerning their products, the distributors may not be aware of the full range of competing products, and, if they do know, may not provide that information to the builders for competitive reasons (Ehrenkrantz Group, 1979). They also have little incentive to pass information back to the manufacturers about builder demands for different products, further decreasing the information available to the manufacturer relevant to the development of innovations.

For some manufacturers, such as lumber and millwork companies, residential construction is their primary market; downturns in the demand for housing directly decreases their sales. This market cyclicity discourages long-term investment in new product development, since market growth for them is less a factor of their market strategy and more a result of overall economic cycles.

Other manufacturers, such as gypsumboard producers, supply several different segments of the construction industry. These firms are less dependent on housing demands cycles, but like the more residential-dependent manufacturers, new product development is seen as secondary to general economic cycles as affecting market growth.

A final type of manufacturer are diversified companies, such as insulation and chemicals producers, for whom the residential construction market is only a small portion of their total sales. While these manufacturers may introduce into residential construction products developed for other industries, they often do not perceive significant benefits from continually developing new products because of the expenses of obtaining code approval and the costs of selling to geographically dispersed and disparate residential builders (Ehrenkrantz Group, 1979).

In general, the major manufacturers of construction components are not very active in developing and offering new products (Tatum, 1986; Ehrenkrantz Group, 1979). The current level of industry expenditure for research and development is estimated at less than 1 percent of sales (U.S. Congress, Office of Technology Assessment, 1987). Compared to other industries, the investment in research and development for construction in the United States is remarkably low; manufacturers in the construction industry invest only .4 percent of the industry's share of Gross National Product in R&D, while the average for all other industries is approximately 2.2 percent (Arditi, 1983).

2.2.4 Residential Construction Builders

There are over 80,000 residential general contractors in the U.S. with full-time employees; an additional number of residential builders are self-employed, and contract their employees on a project basis (U.S. Department of Commerce, Bureau of the Census, 1989). I estimate that the total number of full-time residential builders equals over 120,000.

Most residential construction companies are very small, with over 90 percent employing less than 10 people (Quigley, 1982). Even the largest companies in residential construction command only a small share of the total housing market; the total housing production of the four largest builders in 1988 equalled only 3 percent of total new home construction that year (Table 2.8).

Table 2.8: Market Concentration of Builders of Residential Structures, 1988

COMPANIES	SHARE OF TOTAL OUTPUT	OUTPUT
Trammel Crow Residential	1%	12,932
Ryland Group	1	9,650
NVR L.P.	1	7,920
Cardinal Industries	1	7,401
Total for 4 Largest Firms:	3%*	37,903

*will not add due to rounding; Total 1988 New Residential Units: 1,455,600

SOURCE: Builder, 1989.

Such small companies are extremely sensitive to the cyclicity and seasonality of the construction market. They rarely have the capital resources to last through decreases in demand, and so have scarce resources to invest in long-term innovation development. Their lack of capital also discourages investment in specialized equipment or other real property which cannot pay back the investment within a short time (Manski, 1973; Business Roundtable, 1982; Tatum, 1986).

Residential construction companies are not only small and lacking in capital, but they are also heavily reliant on the skills of their employees; their ability to use innovations is often dependent upon their employees' experience. One study found that the major mode of obtaining information about innovations in the construction industry was through direct experience (Myers and Marquis, 1968). The cost of obtaining this direct experience can be high, however, both for the individual builders and the industry as a whole. These costs include the original and installation cost of the innovation, the risk of failure from an unacceptable innovation, and the time required to test and evaluate the innovation; all of these costs can severely constrain the opportunities for experimenting with innovations (Thomas et al., 1986; Chang et al., 1988; O'Connor et al., 1987).

An additional cost for builders attempting to use innovations is the rapid turnover of employees common throughout the industry (Tatum, 1986; U.S. Congress, Office of Technology Assessment, 1986b). This instability of the labor force discourages the use of innovations by decreasing the probability that a builder will have the same set of employees long enough to recover training costs. A builder is disinclined to invest significant time or resources training employees in the most effective use of an innovation when a local competitor can gain the advantages of that investment simply by employing those workers.

Despite these barriers, residential builders themselves have capabilities that enable them to innovate. They are skilled and experienced at constructing residential units, as certified by local licensing exams. Most builders have some years of college education, and have been in business for over 15 years (Journal of Light Construction, April 1990). Many builders use advanced techniques for their own project management; out of one sample of builders, over 74% used at least one computer for their business operations (Remodeling, May 1990). In addition, they may perceive significant benefits from innovation because of the project orientation of the work.

2.2.5 Project Characteristics of Residential Construction

While the characteristics of the residential construction market, builders, and manufacturers that can impede innovation have often been studied, analysis of the affect of the project orientation of residential construction is rarely done. The nature of a project-oriented endeavor can create specific opportunities for innovation.

Each residential building is unique to some degree, in terms of the requirements of the site, the specific combination of the building systems, and the types of techniques, tools, and people brought together for its erection. For the residential builder, the specific requirements of each project define the selection and employment of technologies and trades; the project "team", which is assembled by the builder and consists of various subcontractors and tradespeople, changes with each construction job. The constantly changing project requirements can encourage innovation by creating new demands for techniques and materials, while also assembling the expertise to meet those demands.

The specific requirements of a structure pertaining to a selected site can create specialized needs for innovation (Tatum, 1986; Chang et al., 1989). For example, soil conditions and temperature variations may require new materials or construction processes for erection and stability of the foundation.

The energy consumption requirements for the dwelling, which are determined in part by accomodation of the specific wind and sun exposures of the site, may encourage innovation in design, insulation, and heat delivery.

Houses are made up of varying sets of specific components which must be integrated on-site by the builders (Tatum, 1986; Business Round Table, 1982a). Although each system is chosen and installed independently, they must perform to a certain level when integrated into an effectively functioning unit, which is the responsibility of the builder; this performance criteria can create opportunities for innovations (Barnes and Ulin, 1984; Ayyub and Haldar, 1985). For instance, the "sick house syndrome", when the interior air quality is poor enough to cause health problems for the inhabitants, is caused by inadequate air ventilation coupled with extensive insulation (Nisson, 1988). The independent choice of insulation techniques is only now seen to closely relate to the also independently chosen ventilation systems. Several innovative techniques and products have appeared to eliminate this "syndrome".

The variation among components may impede innovation, however, by restricting the amount of experience and expertise a builder can obtain relevent to their use. Each building system, such as a heating system, is made up of many components which may be purchased from different manufacturers. The builder may lack the expertise to select among them and evaluate the consequences. The integration is further complicated because the components are installed by different trades at different times (Tatum, 1986). This division of installation activity can impede innovation when changes in one system require changes in other systems; coordinating these alterations requires timely communication of detailed information to all involved trades. Because the knowledge and skill relevant to one trade do not necessarily overlap with other trades, this communication of changes can be difficult and time consuming.

The organization by project allows builders to meet the disparate requirements of constructing specific houses while keeping overhead and other costs low. Because the elements in each project may vary so much from previous projects, a key factor in the development and use of innovations in residential construction is the extensive installed base of experience and skill, as well as knowledge of how the building components relate together to form a habitable dwelling. The project requirements can present significant opportunities for innovation, and the project team can be composed and managed to respond to those opportunities.

CHAPTER 3: STRESSED-SKIN PANELS IN RESIDENTIAL CONSTRUCTION

3.0 Introduction

I use a single innovation which has appeared in the residential construction industry, the stressed-skin panel, as the basis for my in-depth analysis of the process of innovation in this industry. The stressed-skin panel is one example of innovations commercially introduced into residential construction since 1945; Appendix B describes this innovation and 116 others which are permanently installed in a residential structure. As described in more detailed in Chapter 4, the stressed-skin panels are similar to other recent innovations in residential construction. Focusing on this specific example allowed me to examine in detail the processes and activities required to used an innovation. In particular, I was able to identify a full set of user and manufacturer innovations that solved problems which occurred during the implementation of this innovation.

This section provides the technical and market background to understand the significance of the 34 innovations relating to the panels which

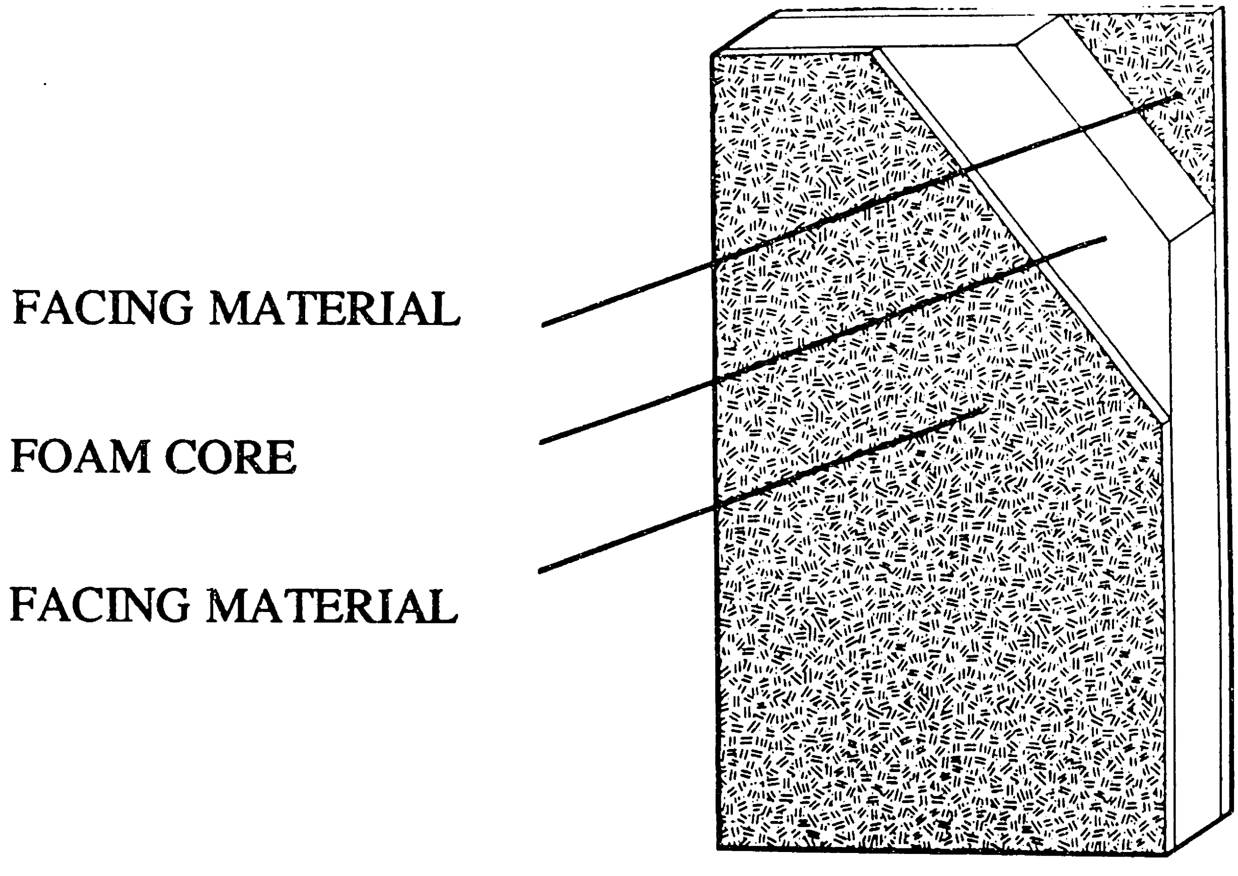
I identified.

3.1 Technical Description of Stressed-Skin Panels

We may describe a stressed-skin panel as a "sandwich" of a solid core of plastic insulative foam laminated to the facing materials, where the facing materials or "skins" carry some portion of the building load. These panels involve a major change in how houses are built. They involve distributing the load of a building over a continuous surface rather than concentrating it in discrete framing members. Adoption of this basic innovation requires the development of many related innovations having to do with accomodating the other elements needed in a house (such as roof framing, interior finish, and electrical systems) to the new design constraints and freedoms associated with the use of stressed-skin panels.

Figure 3.1 shows the basic design of such a panel. The facing materials shown in the figure can be made of plywood, other structural wood sheets, gypsum board, or metal.

Figure 3.1: Composition of Stressed-Skin Panels



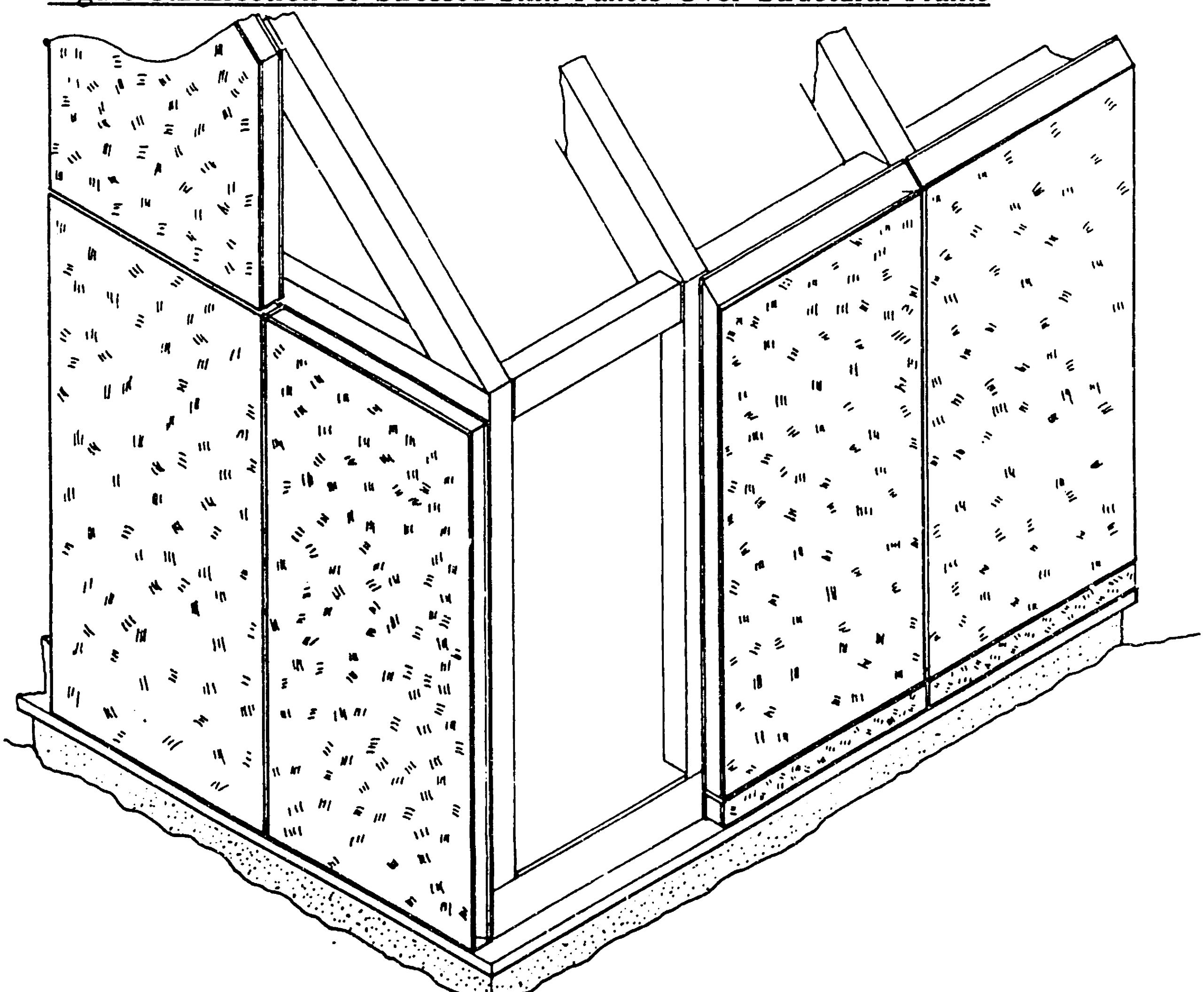
The plastic foam core is not only a connecting web between the facing sheets to distribute the load but it is also a thermal insulating material. The most common types of foam cores are made from polystyrene or urethane (Andrews, 1988; Nisson, 1988). The foam core is the major distinguishing characteristic among the available panels because the polystyrene and urethane foams differ in cost and insulative value. Several claims have been made about the superiority of each of the foams in long-term thermal or structural performance, but they have not yet been verified through independent tests (Andrews, 1988; Nisson, 1988).

Urethane foams have a higher insulative value per cubic inch than the polystyrene foams, but they are also more expensive. For comparable insulative values, the urethane panels are thinner than the panels made with the polystyrene foam, but can often cost 50 percent more (Nisson, 1988; Andrews, 1988; from field interviews). This difference in the depth of the wall panels primarily influences the interior finish of the structure, such as window trim. A long term development which may affect the relative value of the two foams is the chloroflourocarbon (CFC) blowing agent used for the urethane foams is scheduled for elimination by the mid-1990s because of its damage to the ozone level. Replacement foaming agents have not yet achieved adequate insulative ratings or demonstrated their long term chemical stability (from field interviews).

The stressed-skin panels can have either two load-bearing surfaces (called "structural panels") or only one load-bearing surface (called "insulative panels"). Structural panels can carry the full weighted load of a building and thus can functionally replace wood framing; insulative panels can carry only shear stress and are installed over framing members. The erection processes of the structural and insulative panels may differ, but this is the only area of distinction between the two types of panels; their composition and manufacture are otherwise identical, as is the installation of services.

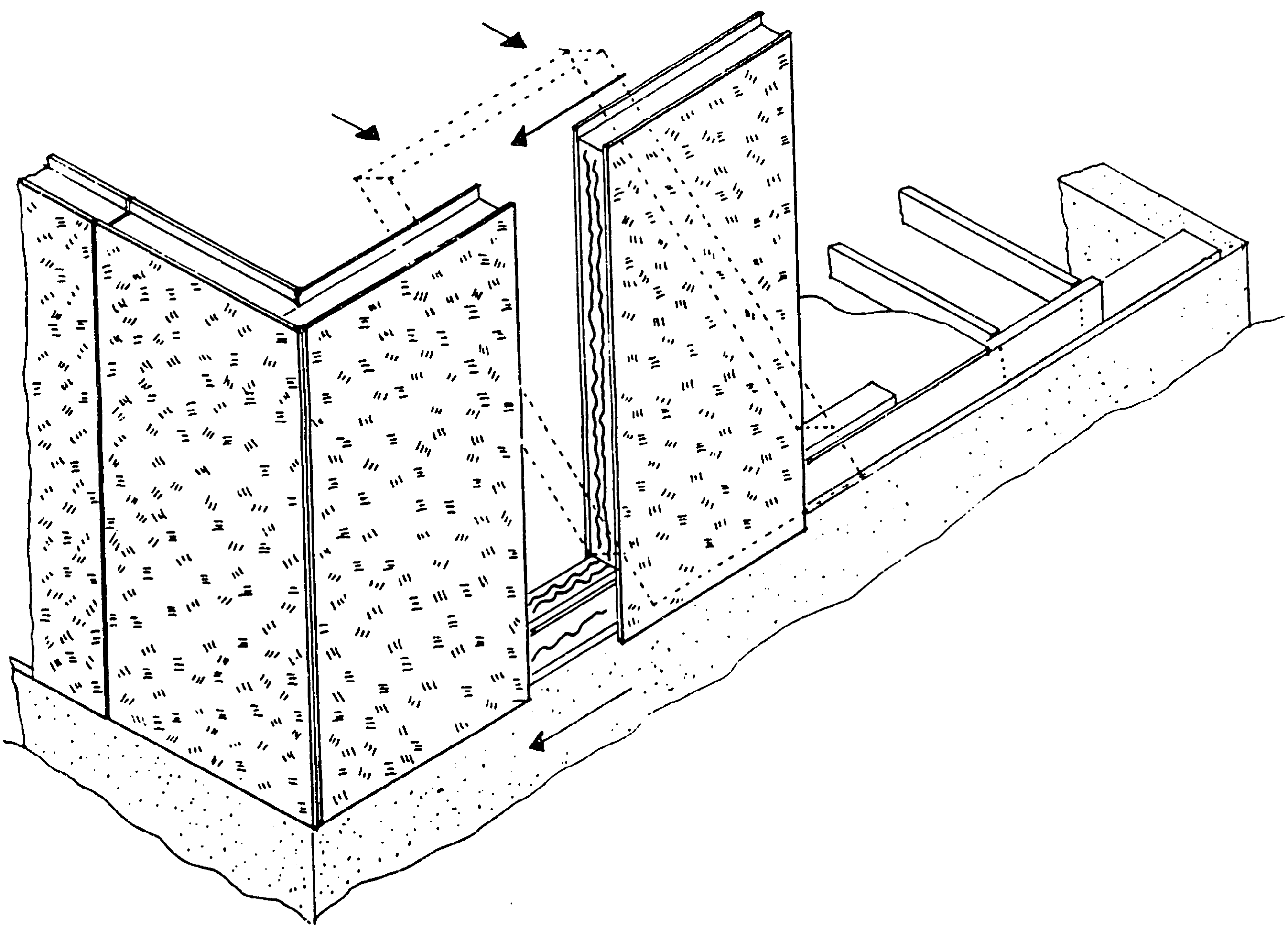
Both insulative and structural panels can be installed on a woodframed structure. The panels are fastened to the exterior of the framing with 6 to 12 inch nails, which are long enough to penetrate the panels and to be adequately imbedded in the framing. Gaps between the panels and the exterior frame surface are sealed with adhesive caulks. Figure 3.2 shows how the panels may be arranged over a structural frame.

Figure 3.2:Erection of Stressed-Skin Panels Over Structural Frame



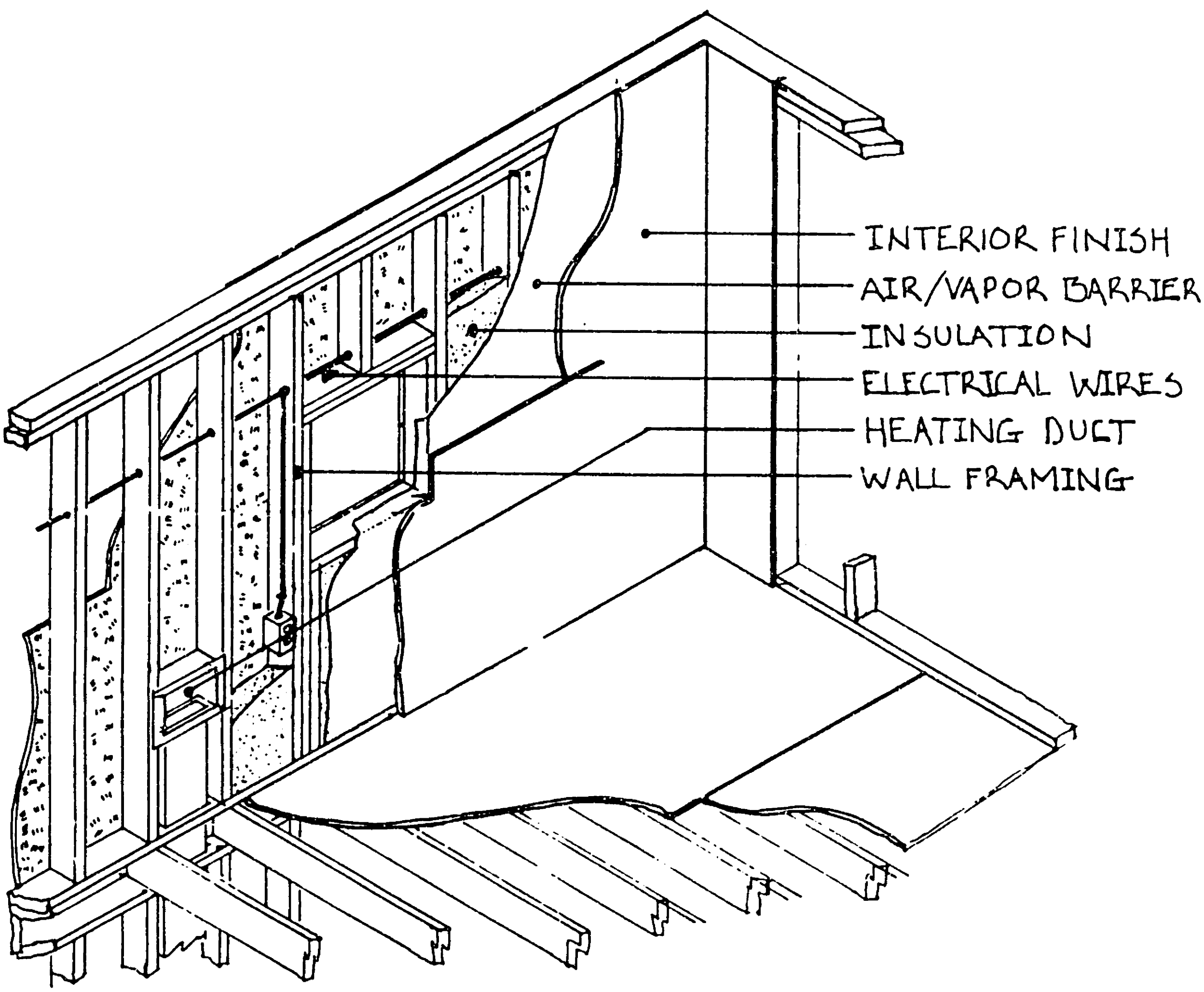
The structural panels can be used without any additional structural framing; they can be erected directly on the floor platform. In this configuration, the panels carry the full load of the building over their continuous surfaces, and the connection between these panels must maintain the surface continuity and prevent buckling under load. If roof panels are used in addition to wall panels, crossbracing from the ceiling or floor joists is required to keep the wall panels from bowing out (Wade, 1985; Andrews, 1988; Carlson, 1988.) Figure 3.3 shows how the structural panels are erected.

Figure 3.3: Erection of Structural Stressed-Skin Panels



The construction process using stressed-skin panels is very different from using standard building materials. Most residential structures in the U.S. are "stick-framed", that is, they use 2 inch thick dimensioned lumber to frame the house structure (U.S. Department of Commerce, Bureau of the Census, 1984). Figure 3.4 is a diagram of the framing and composition of a standard wall.

Figure 3.4: Cross-Section of a Standard Wall Framed with 2 Inch Dimensioned Lumber



The depth of a standard wood-framed wall is slowly built up through successive stages. First the wall is framed, and then sheathed on the exterior using plywood or other structural wood sheets. All services (such as electricity, heating, and plumbing) are then installed within the wall cavity, with notches or holes cut in the "studs" (framing members) where necessary. Doors, windows, and other opening components are then put into place, often just before the insulation is installed in the wall cavities. In most dwellings, an "air/vapor barrier" is installed over the interior framing of the wall, to decrease air infiltration and condensation. The exterior of the house is finished with such materials as siding, clapboards, or shingles. Finally, the interior wall surface, such as gypsum board, is hung off of the studs, and the interior finish (such as trim, cabinets, flooring, and paint) can be completed.

In sharp contrast, the stressed-skin panel encompasses the whole wall depth, from interior wall surface to exterior finish.[1] While a standard wall is slowly built up, the panel is a single unit. Unlike the cavity which exists in a standard wall after it has been framed, the panels have a solid core. Because the foam core and facing sheets work together to carry the load, cuts cannot be made either within the foam core or to the surfaces without altering the panel's load-bearing capacity. Therefore, installation of the standard residential services (such as electrical wiring, heating, and plumbing)

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[1] Some manufacturers offer panels complete with exterior wall finish, though it is not a standard product.

must be specially designed to fit in a panel-enclosed building.

While care must be excercised, cuts in certain areas can be accomplished within certain technical constraints. Openings for doors and windows can be cut in the panels, though extra framing over the opening is required when the span is greater than 4 feet. Small cuts through the panel with a minimum disturbance of the facing sheets for wiring and electrical outlets will not alter the load-bearing capacity excessively. However, most panel manufacturers recommend that no heating or ventilation ducts be installed within the panels themselves, since they may sometimes require a larger hollow in the foam-core than can be safely accomodated. They also strongly recommend against the installation of plumbing in the exterior wall for the same reason.

The panels can provide significant benefits over the previous best alternative for a specific segment of the housing market, the timber-framed house. Timber-framing uses large wooden framing members which act as posts and beams to carry the building load. When panels are not used, a timber-framed structure is enclosed by walls built out of 2 inch dimensioned lumber in between the posts and beams. The walls themselves are highly redundant structures, because they duplicate the function of the beams. In addition, the construction and finish surfacing of these walls is time consuming, and the joints between these "infill" walls and the timbers often crack, leading to air leaks, condensation, and other problems.

The major benefit of the panels for timber framed housing is that they form a continuous thermal barrier on the exterior of the structure, eliminating both the cost and performance problems of the infill walls. They also provide the aesthetic benefit of revealing the timbers in the interior space. A structural advantage of the panels used in conjunction with the posts and beams is that their shear strength capability allows the elimination of knee braces, thereby simplifying the frame joinery, decreasing lumber costs, and reducing erection time (from field interviews).

3.2 Market for Stressed-Skin Panels

The market for insulative and structural panels has grown considerably in the last few years. The estimated 1990 sales of solid foam-core panels produced in the U.S. equalled 19 million square feet, or the equivalent of 5,000 units (from field interviews). While these panel sales equal less than one percent of all new homes constructed that year, the stressed-skin panel manufacturers state that the market has doubled in the past five years. They further predict that it will double again in the next few years, in response to increased costs for fuel, other building materials, and skilled labor. The renovation and rehabilitation market for the panels may increase to exceed that of new construction.

Stressed-skin panels are 5 to 10 percent more expensive than standard built homes in final costs (including erection, enclosure and insulation). The material costs are approximately 20 percent higher than in standard structures, but labor savings are supposed to be significant. The cost of a standard 4x8 panel is between $68 and $72, depending on the type of foam, facing materials, and other variables (from field interviews). The panel manufacturers claim that the cost differential between panel and standard homes can be recouped within 5 years from energy savings (Carlson, 1988).

The insulative panels equalled approximately 50 percent of total panel sales in 1990 (from field interviews). The insulative panels are usually used in new, timber-framed structures, which are only a small portion of all new homes built. Most structural panels appear to be used for additions and renovations to residential buildings rather than for new construction; while the structural panels can replace expensive and time-consuming wood framing, the market does not seem totally accepting of a complete structure which does not have any wood framing.

The market for the panels tends to be geographically constrained because the panels are heavy and relatively fragile; transportation costs can be a significant share of total costs. It appears that the New England region constitutes the largest geographical market, with approximately one third of all panel sales occurring in that region, with an equally high geographical concentration of large panel manufacturers (calculated from field interviews).

Currently, over 100 panel manufacturers exist in the U.S. The majority of these manufacturers are either builders who use the panels that they produce, or ex-builders who now exclusively produce panels. Only a handful of the manufacturers were not originally construction companies; most of these firms came from the refrigeration industry (from field interviews; Andrews, 1988). Among the largest stressed-skin panel manufacturers are Winter Panel, Associated Foam Manufacturers (a consortium of panel manufacturers), Atlas Industries, Foam Products Corporation, Enercept, and Foam Laminates of Vermont. Appendix C lists selected manufacturers of stressed-skin panels; it excludes those builder/manufacturers who only produce panels for their own building projects.

The engineering principle for a stressed-skin panel was adapted from early research conducted in the aerospace industry. The first commercialization efforts failed, however, and the panels were "re-invented" by builders many years later. The current structure of this market reflects its builder origins.

Several attempts were made to introduce stressed-skin panels to the homebuilding market. While "stressed-skin panels" using paper honeycomb cores were first tested for housing in 1935, the first plastic insulative foam core panel was commercialized for residential construction in 1959 by the Koppers Company. It produced panels for homebuilding for only two years; one of its license holders continued to produce panels until it went out of business in 1974, but these panels were limited almost exclusively to refrigeration applications. In 1963, a company called the Alside Home Program produced foam-core stressed-skin panels for housing using advanced automated production systems, but closed after only one year (Andrews, 1989).

The foam-core stressed-skin panels were "reinvented" by builders in the late 1960s. Builders were using the basic materials to insulate roofs, laying blocks of the insulative foam over the roof sheathing, and covering it with another layer of plywood. Eventually, the materials were assembled on the ground as panels by builders; these builders had no knowledge of the previous incarnations of the "stressed-skin panels." The panel fabrication was subsequently moved off-site to improve the panel quality (from field interviews).

The majority of the panels are produced the same way the builders made them on-site; the foam is laminated to the facing sheets using an advanced mastic adhesive. The glued panels are then placed in a press which maintains a constant pressure evenly distributed over the panel surface until the adhesive sets (Arvin, 1985; Carlson, 1988). One manufacturer has developed a different production system, injecting the polyurethane liquid between the facing sheets and foaming it in-place (from field interviews). This production system, while capable of fabricating panels of any size or shape, requires the use of urethane foams, and is currently operating well below capacity, and so has not proved to be a strong competitive advantage for this manufacturer (from field interviews).

CHAPTER 4: METHODOLOGY

4.0 Introduction

I collected the majority of the data for this research through structured interviews with over 50 individuals in the industry, compiling detailed technical and management data about the development and commercialization of specific innovations. The data consists of two samples: 1) innovations permanently installed in residential buildings and commercially introduced since World War II; and 2) innovations relating to the stressed-skin panel.

For this research, an "innovation" is defined as anything new that is actually used; this term has economic origins. In contrast, an "invention" is a term that has legal origins, and is defined as a technical development which meets legally specified standards, such as novelty and usefulness.

In the course of my work I refer to innovations by "users" and by "manufacturers". An innovation can be classified in terms of its relationship to its creator, specifically how its creator appropriates the benefits. If the creator develops an innovation in order to use it, it is a "user innovation." It is a "manufacturer innovation" if the innovation is specifically developed to be manufactured and sold. This distinction is particularly useful in examining innovations which occur during the implementation of a technology, when either the "user" or the "manufacturer" may innovate, but the benefits from the innovation are received through different mechanisms. In the instance of my study, a user is a builder of residential housing, and a manufacturer is a firm that manufacturers stressed-skin panels or other building components for commercial sale.

4.1 Selection of Case

I concentrated on the single industry of residential construction in the United States for this research so I could examine specific innovations, a key aspect of my approach. While the data are predominantly qualitative, they are appropriate for this in-depth examination of user innovation.

I chose to examine residential construction because preliminary study and some anecdotal evidence suggested that innovation is far more prevalent in this industry than is currently believed. Focusing on a single industry allowed me to examine in detail the generation and use of innovations. I limited my case study to the United States to reduce the number of potential factors that could effect the development and use of new technologies in the residential construction industry, such as the involvement of the government in regulation and research funding.

The United States' residential construction industry is similar to that of other developed countries. The techniques, materials, and equipment used in the U.S. are similar to those employed in housing construction in other countries. The wood framing systems which are used for the majority of the residential buildings in this country are found in many other regions, such as northern Europe and Japan. While the dimensions of standard components differ among countries, the materials are remarkably similar (Windborne-Brown, 1984; U.S. Congress, Office of Technology Assessment, 1987; Karn, 1973). In addition, the United States is one of the largest markets for residential construction in the world, second only to the U.S.S.R. in the number of new dwellings built per year (United Nations, 1988). Therefore, trends observed in the U.S. may not only be applicable to other markets, but do in themselves apply to a significant portion of the international residential construction market.

Residential construction differs from many other industries in the U.S. economy in its dependence on skilled labor. The total construction industry (which includes other segments in addition to housing) directly employs at least 5 million people, over 10 percent of the national employed labor force (Predicasts, 1988). These employees are divided among 75 labor specialities, which are organized into 17 craft unions (Ventre, 1979). These specialized trades are organized to maintain and update their stock of relevant knowledge and to train new members in its application. The major category of expenditures in this industry is for labor; unlike many other manufacturing industries, few residential construction companies own production facilities such as plants and warehouses.

Despite its reliance on skilled labor, the residential construction industry can be viewed as representative of patterns of innovation in other industries due to two complementary trends. First, residential construction is beginning to resemble other industries as it decreases its reliance on on-site skilled labor through increasing off-site fabrication of parts and on-site automation (U.S. Congress, Office of Technology Assessment, 1986a; U.S. Congress, Office of Technology Assessment, 1986b; Dowall and Lynch, 1986; Quigley, 1982). These actions are slowly moving the residential construction industry somewhat away from its skill and craft-based orientation and more towards manufacturing techniques and concerns prevalent in other industries. Secondly, as other industries downsize their production runs to meet increasingly complex market demands, they recognize the advantages of increasing the skill levels of their employees, and their methods and outputs may increasingly correspond to those of residential construction (Nelson, 1987; Scott and Lodge, 1986; Piore and Sabel, 1984).

The focus of my empirical research is the specific example of the stressed-skin panel. Despite its fairly recent appearance, the stressed-skin panels are similar to many other innovations in residential construction. First, many recent innovations involve complex theoretical concepts on such issues as heat flow, moisture condensation, and relative air pressure. The engineering concept for the panels is no more complex than those underlying other innovations. Secondly, most innovations in this industry require significant changes in standard practices to accomodate new concepts and materials. While the changes required to use the panels are numerous and complex, they are not unusual.

My narrow focus on the stressed-skin panel and related innovations allows me to analyze exactly what occurs as an innovation is applied and progressively improved over time. Since the sample of innovations relating to the stressed-skin panels has occured relatively recently, I had the advantage of being able to find and interview participants in the various innovations who were, by and large, still working in the industry. In addition, I was able to collect information about both the initial selection and repeated use of the panels because the construction companies are small enough that often the same person who selected the stressed-skin panel to use on a specific project was also responsible for installing it, and thus had to solve any problems which appeared.

The extent to which I can generalize my findings on the basis of this narrow sample is not clear, but I find no obvious sources of bias with respect to the issues I examine.

4.3 Methodology of Data Collection

As the first step of my research, I conducted a comprehensive survey of the literature to compile a sample of innovations in the residential construction industry as a baseline for more detailed analyses. In the second step, I conducted field interviews with builders and manufacturers to construct a sample of innovations related to stressed-skin panels in order to examine innovation by "learning by doing" in depth. Chapter 2 describes the residential construction industry, and Chapter 3 provides the technical and market background of the stressed-skin panels.

4.3.1 Sample of Post-WWII Innovations

I compiled a sample of 117 innovations in the residential construction industry which are permanently installed in a dwelling. These "permanently installed" innovations are those evident after construction is completed, constituting the end result of all of the inputs, such as materials, knowledge, and equipment.

All of the innovations in the sample were commercialized between 1945 and 1990. This 45 year period allows sufficient time for industry testing and acceptance of the innovations. Since over 70 percent of all homes have been constructed since 1945, and the renovation and rehabilitation of older buildings is common, these innovations may be present in virtually all residential units in the U.S. (U.S. Department of Commerce, Bureau of the Census, 1985).

An example from this sample can demonstrate the characteristics of these innovations. Nonmetallic sheathed electrical cable, made by the Romex Company, was developed before World War II, but was not commercially introduced until after the war (Ventre, 1973). The sheathed cable is a significant improvement over the previous best available methods for installing electrical wiring in residential buildings, that is, rigid conduit (a hollow metal tube) or armored cable; it is more flexible, lighter, less expensive, and easier to install than the other methods. It signficantly reduced costs by decreasing the amount of time and labor required to install the wiring.

This sample is a subset of all innovations in residential construction; documenting the full extent of innovative change in this industry is beyond the scope of this study. The sample excludes innovations in the fields of management, communications, information processing, financing, land development, design, appliances, tools, equipment, and materials development. While it does exclude many categories of innovations in the construction industry, this sample can prove a useful model for determining the significance and contribution of all innovations in this industry.

Table 4.1 lists this sample of 117 innovations by functional area. A full description of each innovation is provided in Appendix B.

Table 4.1: Sample of Innovations to the Permanent Residential Structure, 1945 to 1990

FUNCTIONAL AREA	N
Structural exterior wall framing	7
Enclosure and insulation	8
Openings	13
Interior wall framing	7
Foundation	12
Floor framing	10
Roof framing	7
Roof covering	7
Plumbing	12
Electrical wiring	4
Heating/ventilation/air conditioning	12
Interior finish	18
TOTAL:	117

NOTE: Descriptions of each innovation are provided in Appendix B.

SOURCE: Survey of literature.

I constructed this sample using primarily written documents. I conducted a comprehensive survey of the literature to identify innovations which were commercially introduced during the time period. For instance, some books and articles reviewed selected innovations in the industry (Johnson, 1968; Ventre, 1973; Strassman, 1978; National Research Council, 1984; Cook, 1981; Mayer, 1978; Lytle and Reschke, 1982; Emerson and Olesky, 1983; Eichler, 1982). In addition, I used the "new product" sections and articles of various periodicals (such as Journal of Light Construction, Fine Homebuilding, Builder, and Custom Builder).

For each innovation, I identified several operational characteristics, such as its function, degree of technological change from the previous best available technique or product, and associated costs and benefits from its use. Unfortunately, information about the history of each innovation's development, testing, and commercialization, a major focus of this research, was not as readily available.

I checked the validity and comprehensiveness of the sample through review done by several experts in residential construction who have conducted research with respect to new technologies in residential construction. They evaluated each of the innovations in the sample, and their operational characteristics listed above. They provided helpful corrections and additions, and judged the sample to be virtually complete.

This sample has various strengths and weaknesses. Among its strengths are that it provides a comprehensive view, over time, of the incidence of a selected type of innovation in residential construction. It also focuses on specific innovations, their functions and their respective values. One of its weaknesses is that much information about the history of the development and commercialization of the innovations is either undocumented or not available for the public record and so could not be included. Another is the fact that the sample is dominated by innovations which have been commercialized by manufacturers, a constraint mentioned earlier in reference to related research on user innovation.

4.3.2 Sample of Stressed-Skin Panel Innovations

The stressed-skin panel was first commercialized after World War II and has, I find, been improved by 34 separate innovations since that time. This sample includes all the innovations that I was able to identify that have been actually used in construction related to the basic stressed-skin panel (Chapter 3 provides a technical description of the stressed-skin panel.)

Each of the innovations in this sample has been widely adopted by builders in the industry. Some have also been manufactured for sale to builders by manufacturers who supply the housing industry. The sample contains 34 innovations, covering the entire time period of panel use in residential construction, from 1970 to the present day. Table 4.2 lists these innovations, grouped by the function they fulfill. A full description of each innovation is provided in Appendix A.

Table 4.2: Sample of Innovations Relating to Stressed-Skin Panels By Function, 1970 to 1990*

FUNCTION	N
Connection of panel to foundation	1
Connection of panel to frame	3
Connection of panel to roof	1
Structural connection between panels	2
Corner connection between panels	3
Insulated connection between panels	6
Framing of openings within panel	2
Installation of HVAC within panels in construction	2
Installation of wiring within panels in construction	7
Ventilation of roof within panels	2
Rendering panel insect repellent	4
Development of curved panels	1
TOTAL:	34

*1970 is the approximate beginning of the widespread use of the panels in residential construction.

NOTE: Descriptions of each innovation are provided in Appendix A.

SOURCE: Field interviews and panel installation manuals (see methodology).

The data gathered for each innovation consist of qualitative as well as quantitative information relevant to this research; they provide a rich description of the innovations associated with stressed-skin panels, including the conditions and incentives surrounding their creation.

I conducted structured interviews with all of the major participants in the stressed-skin panel industry. They provided the core of my data for the sample of innovations to stressed-skin panels. My interviews included the seven largest panel manufacturers, whose total shares equal over 80 percent of the market; and the seven largest builders who, for an average of 12 years, have used stressed-skin panels for residential buildings. Although the builders I interviewed account for only a small portion of the total market for stressed-skin panels in residential construction (the residential construction industry is quite fragmented), their experience seems to me to be representative of the users in this field.

My interview data was supplemented by two other major sources: a survey questionnaire completed by over 100 builders who use stressed-skin panels; and interviews with experts who have conducted research on residential construction technologies and stressed-skin panels. Company technical and management documents, trade journals and technical publications provided further information on the innovations.

I chose to conduct field interviews because other sources would not yield appropriate levels or types of information. Available industry statistics usually concentrate on the finished characteristics of a residential structure rather than the operations used to construct it. Other industry analyses which do explicitly consider the inputs for construction do not address the processes which effect the value of the output. My research, however, considers the inputs, production processes, and their cumulative effect on the value of the final product.

I judged survey questionnaires inappropriate as a primary source of data because I found that a key aspect of user innovations is the unpredictability of site conditions. For this research, I found that the feedback and response possible through in-depth interviews elicited the detailed information needed for this research about each innovation and the conditions which prompted its creation and commercialization.

The sample of innovations and accompanying information were checked for validity and comprehensiveness through review by builders experienced in using stressed-skin panels, manufacturers of the panels, and experts. They judged the sample to accurate and complete. Industry technical and management documents, trade journals, newletters, and other publications provided an additional check on the data, particularly the identification of innovation sources and time of appearance.

The incidence of these innovations is judged to be sufficient for the purposes of this research. The innovations are not weighted in any way, since the occurence of the innovation alone indicates the appearance of a user need and activity to meet that need. Weighting would not necessarily reflect the value of the innovation to all users in all situations because the implementation conditions of the innovations can vary widely.

The strengths and weaknesses of this sample reflect the data collection method employed. One of the strengths of this sample is that it contains detailed information about each innovation, including the history of its creation, introduction and commercialization as well as its functional and operational aspects. Another is that this technique allowed me to identify all user innovations, rather than being confined to those commercialized by manufacturers. It also covers a sufficient time period for the interview respondants to accumulate experience with the panels and their installation in houses. One of the weaknesses of the data is that in-depth interviewing is time-consuming and resource-consuming, leading to a small sample size. The interviews also produce qualitive information which, together with the small sample size, limit the type and levels of statistical analysis which can be performed on the data. Despite these weaknesses, I could not detect any region of bias which would influence the conclusions drawn from this research.

CHAPTER 5: RESULTS

5.0 Introduction

The three major results of this study both confirm previous research findings and provide new insights. First, I find that residential builders were the primary sources of innovation, creating more than 80% of the innovations studied. The builders created these innovations only for use in their own building projects, and so I term them user innovations.

Second, I find that innovations developed by builders differed from those created by manufacturers. The former often involve physical connections between panel and non-panel building elements, while the manufacturers' innovations were limited to the single component of the stressed-skin panels. Third, I find that manufacturers commercialized only a small portion of all builder innovations, and they did not commercialize innovations pertaining to the connections among systems. In the remainder of this section I will develop and examine each of these major findings in turn.

5.1 Users are the Largest Sources of Innovations

After a detailed study of my sample of thirty four innovations related to stressed-skin panels, I found that 82 percent had been developed by individual residential builders, and 18 percent by manufacturers of stressed-skin panels (Table 5.1).

Table 5.1: Innovations Relating to Stressed-Skin Panels by Function and Source of Innovation

	SOURCE OF INNOVS		
FUNCTION	USER	MFR	N
Connection of panel to foundation	1		1
Connection of panel to frame	3		3
Connection of panel to roof	1		1
Structural connect between panels	2		2
Corner connect between panels	2	1	3
Insulated connect between panels	3	3	6
Framing of openings within panel	1	1	2
Installation of HVAC within panels in construction	2		2
Installation of wiring within panels in construction	7		7
Ventilation of roof within panels	2		2
Rendering panels insect repellent	3	1	4
Curved panel	1	—	1
TOTAL:	28 (82%)	6 (18%)	34

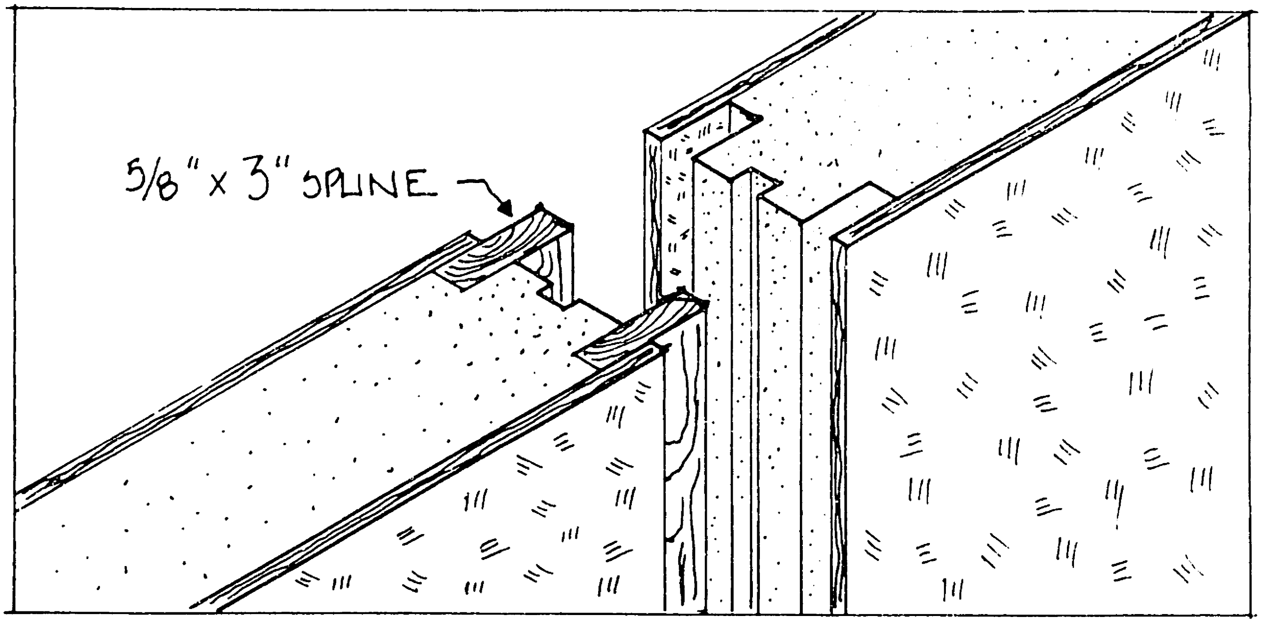
SOURCE: Field interviews and panel installation manuals (see methods).

The importance of user innovation in this industry is further enhanced by two related findings: first, the builders not only innovated extensively in modifying the panel during implementation, but they also were responsible for the original innovation of the panel itself (as dicussed in Chapter 3); secondly, in all cases, users innovated <u>before</u> the manufacturers to accomplish each function listed in Table 5.1. That is, the manufacturers' innovations were essentially functional substitutes for existing user innovations. For each function, the users had solved the problem and used the solution for several years before the manufacturer introduced an innovation which accomplished the same function.

It must also be noted that these manufacturer innovations are not superior, either in technical performance or ease of use, to the user innovations with which they compare. An example from the sample can demonstrate this point.

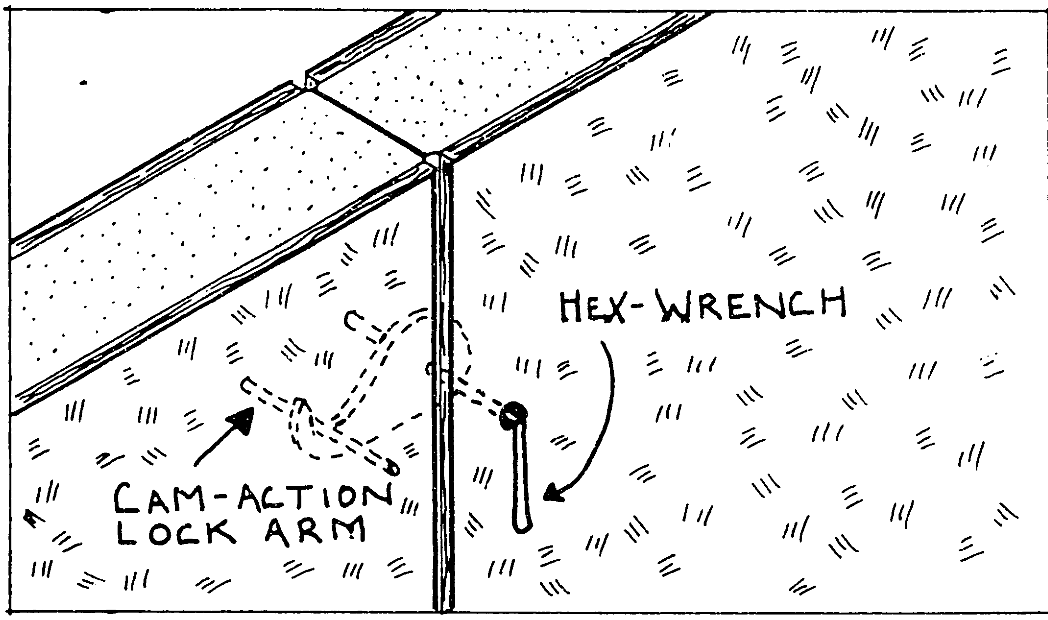
The purposes of an insulated connection between the panels are to provide an barrier to air infiltration as well as to prevent buckling at this joint. One of the user innovations is the in-place foamed spline, which consists of a thin piece of wood which has three grooves routed into its surface. Expanding foam is placed within the grooves, and the spline is slid into a hollow within the panel and screwed to the facing sheets, while the foam expands to create an airtight and thermally insulated seal (Figure 5.1).

Figure 5.1: User Innovation of In-Place Foamed Spline for Insulated Connection Between Panels



A manufacturer innovation for the insulated connection is the cam-lock system built into the panel (Figure 5.2). For this connection, a hooked piece of metal is turned to engage an imbedded metal bar, thereby making a mechanical connection between the panels without disturbing the foam core.

Figure 5.2: Manufacturer Innovation of a Cam-Lock for an Insulated Connection Between Panels



A comparison between the in-place foamed spline and the cam-lock innovations reveals that the manufacturer's innovation is not technically or operationally superior to the user's innovation. While both of the innovations prevent buckling of the panels at this joint, it appears that the air-infiltration performance of the in-place foamed spline is superior to that of the cam-lock, because the splines themselves are a physical barrier to air flow at this joint, and are strongly re-inforced by the expanding foam. In addition, the cam-lock system requires that the panels exactly align for the lock to be engaged, an often difficult maneuver given the unevenness of most building surfaces.

The predominance of innovation in stressed-skin panels by builders is surprising because, on the face of it, builders would be expected to gain less economic benefit than manufacturers from these innovations: residential builders have a very low market concentration while the concentration of manufacturers of stressed-skin panels is very high (Table 5.2).

Table 5.2: Market Concentration of Manufacturers of and Builders Using Stressed-Skin Panels

COMPANY TYPE	SHARE OF TOTAL OUTPUT
4 Largest Panel Manufacturers	77%
4 Largest Builders using panels	1%

TOTAL 1990 SALES: 5,000 units

NOTE: Panel sales are converted to equivalent number of residential units using the average enclosed square footage.

SOURCE: Field interviews.

From considerations of appropriability of innovation benefit, one would expect that the manufacturers in the highly concentrated panel manufacturing industry would expect to garner greater benefits from innovations through their market shares than would even the largest builders in the very fragmented panel user industry (Schumpeter, 1942; von Hippel, 1988). With these relative levels of expected benefits and their strong market position, the manufacturers might be predicted to be the major sources of innovations.

Yet this research reveals a different pattern, where the small building companies with insignificant shares of the stressed-skin panel market are the major sources of innovations in the panels. The benefits which the builders receive from these innovations must therefore include other factors than market power alone.

To explain the far greater number of innovations from the users than from the manufacturers, alternative incentives and the mechanisms for appropriating these benefits need to be examined in depth. Three principal causes were identified: (1) the cost of user solutions is low; (2) the cost of delay for users is high and manufacturer solutions delivered to the site would take longer than would the creation of local user solutions; and (3) the cost of regulatory approval is less for users than for manufacturers.

5.1.1 Cost of Finding Solution

In the sample I studied, I found that all user innovations to stressed-skin panels had important attributes in common. First, they were ad hoc responses to problems encountered in the course of a construction project that an innovating builder was engaged in. They were emphatically not "R&D projects" in any formal sense. The innovations were also very rapidly fabricated and installed at a low cost, using materials and equipment on hand at the job site. Clearly, this picture conforms to the findings of research on problem-solving that concludes that solutions are often sought first from the resources immediately available and from recent experience (Marples, 1961; Allen and Marquis, 1964; Bergen, 1984).

In the instance of the 28 innovations in stressed-skin panels created by users, the time from discovery of the problem to installation of the completed solution on the site was only 1/2 a day on average (Table 5.3). The total cost of each innovation, of time plus equipment and materials, was very low, averaging only $153. Table 5.3 lists the actual elapsed time from perceiving the problem and achieving and installing the solution on-site, as well as the total time and material cost for the builder innovations. The costs for each innovation are averaged within each functional category shown in Table 5.3.

Table 5.3: Innovations Relating to Stressed-Skin Panels: Average Actual Cost of User Innovations Installed On-Site by Function

FUNCTION	Average Elapsed Time (days)	Average M+T Costs	N
Framing of openings within panel	1/10 DAY	$20	1
Structural connect between panels	1/10	30	2
Ventilation of roof within panels	1/10	32	2
Insulated connect between panels	1/10	41	3
Corner connect between panels	1/5	60	2
Installation of HVAC within panels in construction	1/5	60	2
Installation of wiring within panels in construction	1/5	79	7
Connection of panel to roof	1/5	80	1
Rendering panels insect repellent	2/5	123	3
Connection of panel to foundation	1/2	160	1
Connection of panel to frame	1 1/5	377	3
Development of curved panel	5	1,500	1
AVERAGE INNOVATION TIME AND COST FOR ALL FUNCTIONS:	1/2 DAY	$153	(28)

NOTE: Cost of innovation calculated from material and equipment cost plus labor cost valued at $280 per work day.

SOURCE: Field interviews and Means (1989).

Let me provide an example of a builder innovation, to convey their flavor:

Example: A novel, builder-developed method for installing a wall switch in a stressed-skin panel

Faced with the immediate problem of installing a wall switch in a stressed-skin panel, a builder devised a means of cutting a hollow in the foam at the center of the panel that would accomodate a switch box and related wiring. His method had the advantage of not cutting the panel facing sheets, and involved melting the foam with a heated wire. This method is now widely used by builders.

The builder-innovator reports that the total time that the innovation took was only an hour, and the total cost for time and material equalled $40.

5.1.2 Cost of Delay

Any delay in obtaining solutions to problems can have high costs for a builder, since delays mean that work crews are not completing tasks, and the schedule of deliveries, subcontractors, and other activities must be altered to reflect the changed timetable. Even if a manufacturer learned of the need for an innovation as soon as a user discovered it, and even if the manufacturer's costs and times for developing an innovation were as low as those shown on Table 5.3, above, the manufacturer's off-site location means that a manufacturer could not deliver the innovation to the builder as rapidly as the builder could build it "on the job".

In the case of the stressed-skin panel-related innovations, the average delay for the manufacturers to respond to identified problems is estimated at over 40 work days, which can be valued at $280 a workday in lost costs for the builder. While it is doubtful that a builder would actually delay construction for that long waiting for the manufacturer to solve a problem, the estimation of the costs can provide a basis on how the builders value their alternatives.

Table 5.4 presents the estimated delay time for the manufacturer to make and deliver a solution to the site. This is a conservative estimate because it excludes any time for innovation problem-solving, considering only the amount of time required to actually fabricate a product incorporating the innovation and deliver it to the site. [2] As shown in Table 5.4, a delay of at least five days would be necessary for the manufacturers to solve even the easiest problem, fabricate a panel and deliver it to the site (from field interviews). This delay can be valued at the cost to the builder for crew down-time and rescheduling. More complex problems would entail longer delays and thus have greater costs for the builders.

[2] This cost of delay does not include any extra costs charged for solving the problem (some firms charge $50 an hour for engineering time), and it does not include customization costs for a special order panel.

Table 5.4: Innovations Relating to Stressed-Skin Panels: Average Estimated Cost of Delay for Builders by Function

FUNCTION	AVERAGE TIME	AVERAGE DELAY COSTS
Connection of panel to foundation	5 DAYS	$1,400
Framing of openings within panel	5	1,400
Connection of panel to frame	10	2,800
Corner connect between panels	10	2,800
Connection of panel to roof	10	2,800
Installation of wiring within panels in construction	10	2,800
Installation of HVAC within panels in construction	10	2,800
Structural connect between panels	10	2,800
Insulated connect between panels	10	2,800
Development of curved panel	100	28,000
Ventilation of roof within panels	100	28,000
Rendering panels insect repellent	250	70,000

AVERAGE TIME AND DELAY COST FOR ALL FUNCTIONS: 44 DAYS $12,367

ASSUMPTIONS: 1) Manufacturer willing and able to provide an innovation for each function; 2) minimum response time for manufacturer to solve problem, fabricate panel and deliver to site is five days.

NOTE: Cost of delay to builder calculated at $280 per work day from crew down-time and rescheduling, estimated from industry average of cost per workhour for appropriate crew.

SOURCE: Field interviews and technical manuals; Means, 1989.

Let me provide two examples, wall switch wiring and ventilation of roof panels, to demonstrate how I calculated the costs of delay shown in Table 5.4.

The delay for a manufacturer to deliver a panel incorporating the innovation (mentioned earlier) enabling the installation of a wall switch in a stressed-skin panel would be at least five days. The cost of delay would include re-scheduling the electricians and interior finish crews whose work depend upon the completion of this task. The steps the manufacturer would take (from interviews) during this five-day period would be: 1) receive information on switch location; 2) make panel; 3) create hollow for switch; and 4) deliver the panel to site. The cost of the five day delay for the builder has a value of $280 per workday or $1,400.

The second innovation (developed by a builder) involved the reduction of heat in panels used as roofing via the construction of air channels for ventilation. The innovating builder quickly achieved this function on his job site by using appropriately-oriented thin strips of wood (wood strapping) along with properly-located vents. If a manufacturer were to attempt to fabricate a panel containing an innovation of this same function (and this step was eventually taken by some panel manufacturers), it would take an estimated minimum of 100 workdays.

The estimated elapsed time is longer in this instance than in the instance of the wiring innovation mentioned above because more complex design and fabrication stages would be required. A manufacturer would need to complete the following stages: 1) estimate performance criteria; 2) design panels; 3) perform engineering analysis of panel strength, bending, and other specifications; 4) change panel production system; 5) make panel; and 6) deliver the panel to site.

The cost of 100 days delay to the builder are valued at $280 a workday, with a total cost of $28,000. These costs would include crew down-time and rescheduling of carpenters, roofers, and exterior finish crews.

5.1.3 Cost of Regulatory Approval

The final cause that explains the high incidence of innovation by users relative to manufacturers is that the costs of obtaining regulatory approval are in general lower for the user than for the manufacturer. I have identified two reasons for this.

First, applicable regulations place a far greater burden on the manufacturers who develop and sell innovative products than on the builders who may develop and use such products; the builder either can demonstrate that an innovation meets the specified code or performance requirements, or can provide field test evidence to the satisfaction of the local inspector (Ehrenkrantz Group, 1979; Duke, 1982). In contrast, manufacturers delivering products can be required to provide test data demonstrating code compliance for each locality served (Duke, 1988). Testing new products for compliance in a given locality can take from 1 month to several years, and explicit code approval often takes several additional years (Ehrenkrantz Group, 1979).

Second, the nature of liability is different for builders and manufacturers. In construction, "the contractor does not guarantee a satisfactory result [with respect to a manufacturer's product, but] merely warrants that he will perform the project and install the systems in a workmanlike manner...[In contrast] manufacturers can be found liable [under negligence in] defective design and failure to warn users...the manufacturer warrants that the goods are fit for the particular purpose" (Barnes and Ulin, 1984).

5.2 Innovations Developed by Users Differ Significantly from Those Developed By Manufacturers

As can be seen in Table 5.5, half of the user innovations concern the connection of the panels to other systems, while none of the manufacturer innovations extend beyond the single component of the panel itself.

Table 5.5: Innovations Relating to Stressed-Skin Panels: Innovations by Type and Source

TYPE OF INNOVATION	SOURCE OF INNOVATION USER	MFR
Panel-related only	50% (14)	100% (6)
Connection of panel to other house components	50% (14)	0% (0)

SOURCE: Field interviews.

Panel-related innovations are those that concern only the panels themselves, such as their shape, or the fastenings between the panels. Connection innovations can be explained as follows: in order to use stressed-skin panels in a structure, the panels must be connected to other structural systems, such as the foundation and the framing for the floors and the roof. Panels must also accomodate the services, such as heating and electricity. Innovations that accomplish these functions are coded as "connection" innovation in Table 5.5.

Two examples of a user and manufacturer innovation for the same function, the corner connection between panels, can demonstrate this difference. The major objective of the corner connection is provide a strong tie between panels at this joint. The manufacturer innovation for this function is metal brackets which wrap around the panels at the corner (both inside and outside the structure) and which are screwed to the facing sheets. The user innovation is an "open corner" design, where the panels are pulled back away from the building corner and the insides of the panels are sealed with 2 inch dimensioned lumber which is attached to the floor deck and the facing sheets; this corner space can be used to install wiring, heating ducts, or other services. Even for this connection that is technically only panel-related, the builders have availed themselves of an opportunity to connect with other building components.

I argue that builders innovate in the connections of the panels to other components while the manufacturers do not for three reasons: 1) the integration of the components requires specific and timely information; 2) the integration entails specialized applications; and 3) it may significantly extend regions of liability. These three causes reflect the increased complexity inherent in combining different components, and can help explain the absence of manufacturer innovation on connections.

5.2.1 Specific and Timely Information

A manufacturer wishing to innovate with respect to the connections among components must obtain information regarding the components' composition and performance requirements. This information may change often and quickly, depending upon the environment and any shifts in operational requirements. The user not only has immediate access to this information, but may also be able to excercise some degree of control over the forces provoking the changes. The manufacturer does not and cannot.

More difficult than both the quantity of detail and the frequency of changes is the fact that much of the information is not specifiable. The reasoning that guides the problem-solving for these connections is not explicit; it often relies upon constant feedback through trial and error, informed by experience and judgement (Polanyi, 1958; Mitroff, 1968; von Hippel, 1990). Because the manufacturer is separated from the source of this information (that is, the application stage itself), any information that the manufacturer receives must be translated and transmitted, and any information which cannot be specified is thereby lost (Teece, 1981). Continuing attempts to gather or infer this missing information will only increase costs for the manufacturer and increase the possibility of using wrong information; in von Hippel's terms, the information is "sticky" at the user's site (von Hippel, 1990).

For example, when the panels are connected to the foundation or the floor decking, the information required is not only detailed but also nonspecifiable. Much of the details concern the exact technical dimensions of the foundation; the required information may also involve a judgement of the levelness of the foundation height from the ground as well as the unevenness of the connecting surface itself.

The advantage that builders have over manufacturers with respect to this information explains in part why the users, rather than the manufacturers, create innovations which connect separate components. Some researchers hypothesize that the difficulty and cost involved in transmitting this type of information can determine the locus of problem-solving (von Hippel, 1990; Clark, 1989). This hypothesis appears to be confirmed from these results.

5.2.2 Specialized Application

Innovations that connect different systems are more specialized in their applications than innovations confined to the panels themselves because the connections must fit the specific configuration of components. The integration of the parts not only concerns the specific region of intersection, but also how the separate parts work together as a unit. Seemingly minor changes in one part can require major complementary changes in other parts and the system overall (Henderson and Clark, 1989).

For the manufacturer, attempting to change a product to meet specialized applications may greatly increase the complexity of their product development. Special interfaces may be required to connect the product to each selected component. Given the variety of other systems which could be connected into the panels, the range of specialized applications is usually too broad for the manufacturer to anticipate.

In contrast, the builder's normal activities involve integrating the various components into a fully functional residential unit, so they are more likely to accomplish this activity with a minimum of disruption of their work routines. In the builders' operations, there are no formal separations between integrative activities and other value-adding activities on the construction site. Recognizing and coping with specialized applications is a common activity for the builders because each construction project is unique to some degree (Tatum, 1986). The various elements which make up the productive capacity of the builders (such as equipment and skills) are eminently adaptable to special connection requirements that arise from the selection of specific components.

For example, the heating and ventilation systems in a residential structure are complex and highly interrelated, but are often selected as discrete components. In addition to a centralized heat source, such as a furnace, most new homes also include some mechanical ventilation systems which can provide fresh air while recovering some heat lost through waste air, such as air-to-air heat exchangers. The integration of these different systems will entail the specialized location of air-intake ducts with respect to heat supply sources, customized to the design requirements of the structure.

Not only are the individual units different in their functional requirements and performance, but their specific configuration is unpredictable across different home designs. For the heating component manufacturers, this variety of configurations is unpredictable and therefore costly for them to attempt to anticipate with special components, while the builders can easily accomodate the specialized placement of the ducts and components within the building structure.

5.2.3 Extended Liability

The potential liability for manufacturers who commercialize connection innovations includes not only the manufacturer's own products but also those that are physically connected to these products. That is, the liability is expanded to include an implied warranty of the other system and/or the specific connections. If a manufacturer commercializes innovations that connect systems, it could be interpreted as warranting that the goods (in this case, the product, connection, and <u>all</u> systems connected) are fit for the user's purpose (Barnes and Ulin, 1984). This expanded liability over systems and installation over which the manufacturer has little control is not attractive to most manufacturers.

The nature of a builder's responsibility does not significantly change with respect to specific connections because the standard activities of the construction firm encompass both the customization of components and the integration of the different parts (Duke, 1988; Ehrenkrantz Group, 1979). The builder has a legal responsibility to construct a habitable dwelling "in a workmanlike manner", which includes obtaining and installing all of the different parts and systems.

Thus, while manufacturers observe a significant increase in the region and scope of their liability with the addition of explicit connection of their product to other components, the builders do not perceive a similar increase in their legal responsibility when they connect disparate building components.

5.3 Manufacturers Commercialize Only a Small Portion of User Innovations

Out of the 28 user innovations, I discovered that the manufacturers commercialized only 29 percent. Though user innovations constitute over 80 percent of all innovations to the stressed-skin panels, the manufacturers do not commercialize many of these existing solutions to problems (Table 5.6).

Table 5.6: Innovations Relating to Stressed-Skin Panels: Commercialization of User Innovations by Manufacturers

USER INNOVATIONS	SHARE OF TOTAL
Commercialized by Manufacturers	29% (8)

SOURCE: Field interviews, and industry technical and management documents.

Manufacturers also limit themselves to only commercializing those innovations that concern the panel alone. Out of the thirty four innovations in the stressed-skin panels, 93 percent of the innovations that the manufacturers commercialized were related to the panels alone. Table 5.7 presents the innovations commercialized by manufacturers by type of innovation.

Table 5.7: Innovations Relating to Stressed-Skin Panels: Innovations Commercialized by Manufacturers by Type of Innovation

TYPE OF INNOVATION	SHARE OF TOTAL
Panel-related only	93% (13)
Connection of panel to other house components	7% (1)
TOTAL:	100% (14)

SOURCE: Field interviews and technical documents.

The only manufacturer commercialization of a user innovation concerning a function outside the panels is a minor addition that doesn't really change either the basic functions of the panel or its connections to other components. (This exception to the general pattern concerns the modification of panels to ease the installation of electrical wiring.)

I propose that the major cause for the low rate of manufacturer commercialization of user innovations involving connections between panels is that the market for any one such innovation is small relative to the market for within-panel innovations, but that the design cost for both is similar. (These costs may include obtaining regulatory approval.)

My interviews show that manufacturers of stressed-skin panels do perceive only a very small market for the innovations that connect panels to other components. The largest 3 manufacturers (who constitute over 70 percent of the market) regard these as "custom orders", and state that custom panel sales equal less than 5 percent of their total annual sales. [3] They also state that they would be unwilling to change the basic panel they produce in any of its elementary performance characteristics, and yet virtually all of the connection innovations would require just such modifications.

User innovations that are not commercialized by manufacturers are still produced by users on a regular basis. Typically an individual builder-user

[3] This figure excludes panels cut to specific sizes, and primarily entails customized location of electrical wiring chases.

will have a portfolio of user techniques, and manufacturer-commercialized ones for functions where these are available, that he chooses among as a function of the particulars associated with a specific construction project. The builders surveyed have used most, if not all, of the innovations in this sample at one time or another, and expect to use them in the future (from field interviews). Maintaining this portfolio can provide the builder with greater flexibility than a single method alone can in meeting specialized requirements and changing specifications.

CHAPTER 6: DISCUSSION AND CONCLUSION

6.0 Discussion

One of the principal findings of this research is that, for the sample of innovations examined, users innovate far more than manufacturers do. Analysis reveals that the incentives for the users to innovate are more complex than previously understood. Users respond to particular conditions inherent in applying technologies; the high cost of any delay and access to specific and timely information provide special incentives for the users to innovate. User innovation in this field may thus be seen as an efficient market response to needs which arise during the implementation of a technology, rather than a failure on the part of manufacturers to respond to identified needs.

The research I have reported on here has focused on the implementation stage of a technology, and the process of "learning by doing" by the users as an effective means of accomplishing specialized applications. By examining a full set of innovations, which relate to a specific technology and originate from both manufacturers and users, we can expand our empirical understanding of this phenomenon and begin to develop a broader theoretical framework to encompass the complex incentives that affect user innovation.

It is interesting to note that we have found a high level of innovation in general and user innovation in particular in the residential construction industry; conventional wisdom asserts that little innovative activity comes from this industry overall. As discussed in Chapter 2, significant barriers to innovation clearly do exist in this industry, especially for builders.

Despite these factors, I have found that users innovate far more than manufacturers do. In the sample studied in this research, users created over three quarters of all of the innovations studied; similarly strong patterns have been identified in other industries as well (von Hippel, 1988). The three specific reasons which explain the greater incidence of innovation by users are the low cost of user solutions, the high cost of delay for users, and the low regulatory burden for users.

In the sample of innovations relating to the stressed-skin panels, the users rapidly innovated, making use of materials and equipment at hand to quickly develop and install innovative solutions to problems which appeared while the work was in progress. The solutions were not only adequate to solve the immediate problem, but were effective enough to be adopted as a standard solution by the users. In contrast, if the users had appealed to the manufacturers for the solutions, <u>even if the innovation time and cost are</u>

assumed to be equal for the user and manufacturer, the manufacturers would face a significant delay in producing a product which incorporated the solution and delivering it to the work site. This potential cost of delay is sufficient to encourage the users to innovate for themselves despite the potential costs and barriers.

The cost of delay coupled with the availability of low cost user solutions may be widely applicable in predicting the locus of innovative activity. When the cost of delay is consistently high and low cost solutions are possible, users could be expected to innovate far more than the manufacturers because any delay from problems encountered during the implementation of a technology may have costs far in excess of any actual or potential costs incurred from innovating. In such a condition, the users would be expected to innovate to solve the problem and resume the work in progress as quickly as possible. This prediction contradicts standard theories concerning the distribution of benefits from innovations, as well as studies of the residential construction industry; it does, however, help explain the pattern observed in this research of user innovations vastly outnumbering manufacturing innovations.

The second principal finding of this research is that users innovate on the connections among components while manufacturers do not. This is the first time that a significant difference between user innovations and manufacturer innovations has been demonstrated. The three principal causes identified that explain this disparity between user and manufacturer innovations on the integration of components are the users' access to specific and timely information, their ability to meet specialized applications, and the extended liability that may apply to manufacturers' innovations on connections.

Users innovate on these connections because they possess specific and timely information about the implementation of the technology. The manufacturers, on the other hand, are removed from these application activities and from the source of the information. When they regularly face specialized applications, users would be expected to have standard methods of obtaining and using this vital information. While some types of users accomplish specialized applications as part of their normal routines, most manufacturers are organized around product classes, and view changes to accomodate special applications as "custom orders", that is, service outside their standard operations. Information for the "custom orders" is often gathered and used by different people within a manufacturing company than those who are responsible for normal product specification. This division of information and application compounds the problems encountered in collecting the data for the manufacturer.

It could be said that the integration can't be done without the information, but the information can't be obtained without the integration. In such a case, the user would be predicted to be the sole source of innovations which require this information. This research confirms that prediction, since it found that users are the only source of innovations concerned with connecting the separate components into a whole unit.

Under such conditions, manufacturers cannot necessarily share in the benefits that users receive from innovating. The fast response that the users accomplish by innovating themselves is not available to the manufacturer. The cost of the same solution created by a user is much higher for the manufacturer, who doesn't possess the same set of experiences and materials that render the solution low cost for the user. In addition, when the manufacturer faces a larger potential cost for meeting specialized applications and the code regulations than the user does, even if the innovation is exactly duplicated, the cost of delivering it to local markets is thereby far higher for the manufacturer. Under such conditions, the manufacturer would not be expected to commercialize many of the users' innovations--and indeed, this research found that manufacturers commercialize only a small percentage of all user innovations.

This research reveals patterns of user innovation and differences between user and manufacturer innovations which were previously unexplored. It also identifies causes for these results as a first step in the further exploration of innovation during the implementation stage of a technology. I cannot yet weigh the relative influence of any of these specific causes, but their explanatory power does expand our consideration of the forces operating on users during innovation through learning by doing.

6.1 Conclusion and Future Research

The major conclusion from this research is that users can be significant sources of innovation, especially during the implementation stage. Not only may they innovate far more than manufacturers to solve problems which appear, but they also may produce distinctly different innovations than the manufacturers.

These conclusions do not seem to be dependent upon the age of the specific innovation, that is, the stressed-skin panel. The stressed-skin panel has been in widespread use for residential buildings for over twenty years, and innovation relating to the panels is still occurring. In addition, other technologies in residential construction exhibit the same patterns of continual innovation during implementation; for instance, the "stick-framing" technique of building using 2 inch dimensioned lumber originated in the late 1800s, but innovations continue to appear relating to this technique, as can be seen in

Appendix B.

The research conclusions also do not seem to rely upon the nature of the industry chosen. Similar patterns of user innovations have been observed in industries ranging from scientific instruments and pultrusion processes (von Hippel, 1988) to teaching programs (Johnson and Brown, 1986) to software programs (Voss, 1985; Feld, 1990). From these studies, it appears that the incidence of user innovation is independent of whether the industry is "high-technology" or not.

The expertise of the users with respect to the specific technology being implemented also does not seem to influence the amount of innovation. While the builder-users are sophisticated with respect to constructing a residential building, they are not necessarily experts in the engineering or materials aspects of stressed-skin panels. This lack of specific knowledge does not seem prohibit their innovating. This observation is confirmed by findings in other studies (Voss, 1985; Feld, 1990).

These conclusions may be most relevent where the users are sophisticated with respect to the total system, and where they themselves integrate the disparate components into an operational whole. The results may be most generalizable where the users possess a basic capability to solve the problems that they identify. For instance, the cost of the solutions developed by users depends upon their store of knowledge and experience upon which they draw, which can often not be exactly measured through such factors as the amount of time and materials used.

One of the major implications of this research is a "de facto" design partnership among users and manufacturers. Users receive benefits and possess capabilities which are unique to their implementation role, and the asymmetry of the information accessible to users and manufacturers can be an essential part of making this design partnership work for both sides. In many situations, the users may produce innovations which are essential for achieving a successful implementation, particularly in the integration with other components. In these situations, the users may well solve problems that the manufacturers did not know existed.

A second implication of this research is that the specification of the connections among components will emerge as an increasingly critical area requiring the management of technological change as components are produced in many different locations around the world, and as production in manufacturing moves towards smaller batches. Recognizing the interdependence of the integration of components with the specific information required can reshape the assignment of resources and responsibility essential in accomplishing the formation of a whole operational unit. The contribution of user innovations can be significant in this arena, unattainable through any other means.

Finally, the results from this research imply that the product development process or the product itself can be modified to take advantage of user innovations. These innovations are often technical changes that are already designed, tested and applied by the users and can be readily incorporated into the manufacturers' products. The resulting product alterations may not only be available at lower cost to the manufacturer but may also meet the needs of the users more exactly, and thereby potentially reduce the time required for the product to move through its successive design stages.

Further research remains to be done on innovation during the implementation stage through "learning by doing". First, future research can explore the pervasiveness of innovation by users during implementation in industries other than construction. Do other industries exhibit the same "division of labor", with the users solving most of the problems which appear when the innovation is actually used? Are the same patterns of user innovation evident throughout the effective lifespan of an innovation, that is, as it matures and becomes standard? Do users innovate as much if their role as the "system integrator" diminishes?

Secondly, the strength of the causes identified in this research can be tested, that is, the relative explanatory power of the cost of delay, the cost of finding solutions, the role of specific and timely information, the unpredictability of specialized application, and the influence of regulatory costs and liability. Does the access to specific and timely information consistently provide the user with a problem-solving capability relevant to implementation innovations superior to that of manufacturers? Do high delay costs for the users prompt significant user innovations, even if low cost solutions are not readily available? Does the unpredictability of the specialized applications influence the prevalence of user innovation, even if the costs of delay are not high? Under what conditions are the costs for obtaining regulatory approval lower for the user than for the manufacturer?

A third area for further research is the potential responses by manufacturers to user innovations during implementation. Do manufacturers perceive benefits or increased liability risks from multiple user innovations? Do a manufacturer's maintenance costs for the basic product increase or decrease in the presence of user innovations? How often do user innovations offer the opportunity for commercialization through later product cycles? Can a manufacturer reduce the cost to users of innovating through the redesign of the product? Does this increased accessibility to user innovation also decrease the manufacturer's own redesign and modification costs?

Finally, the contribution of user innovations to the general acceptance of the product can be examined in future research. Do user innovations regularly contribute to either the quality or the basic functions of the product?

Is the perception of rapid and easy innovation an advantage for potential customers or is it viewed as an added cost for implementation? Is the product that attracts high numbers of user innovations more widely accepted in a market, and more profitable, than one which does not permit innovations? Finally, do the user innovations constitute cumulative learning for either the individual user or for the industry as a whole? How does this occur for innovations which are not commercialized (and thereby distributed) by manufacturers?

This research undertook the ambitious task of expanding our understanding of what actually occurs during the implementation stage of a technology, and specifically the values and characteristics of users' innovations. It is only a first step at examining this complex issue, but continued research in this area may improve both the original design process and achieved outcomes of the development and use of innovations.

Appendix A: Innovations Relating to Stressed-Skin Panels by Function, 1970 to 1990

A.1 Introduction

The innovations in this sample relate to the installation and operation of stressed-skin panels in residential structures.

We may describe a stressed-skin panel as a "sandwich" of a solid core of plastic insulative foam laminated to the facing materials, where the facing materials or "skins" carry some portion of the building load. The panel acts similarly to an I-beam to distribute the load. These panels involve a major change in how houses are built. They involve distributing the load of a building over a continuous surface rather than concentrating it in discrete framing members. Adoption of this basic innovation requires the development of many related innovations having to do with accomodating the other elements needed in a house (such as roof framing, plumbing, and electrical systems) to the new design constraints and freedoms associated with the use of stressed-skin panels. Chapter 3 describes the technical characteristics of the panel.

The foam-core stressed-skin panel was first commercialized after WWII and has, I find, been improved by 34 separate innovations since that time. This sample includes all the innovations that I was able to identify that have been actually used in construction to improve the basic stressed-skin panel. Chapter 4 provides the methodology for the data collection of this sample.

I identified the innovations by asking panel manufacturers and builders who use the panels to describe the technical and operational characteristics of the panels. For instance, I asked how they installed electrical wiring in a panel-enclosed house. After the innovation was described in detail, I asked the interview respondant for additional information, such as where the innovation originated, how it was developed, and how often they used it themselves.

This sample of innovations relating to the stressed-skin panel was checked for validity and accuracy through review by builders who have used the panels, panel manufacturers, and experts in homebuilding and stressed-skin panels. They judged the sample to be accurate and complete. Company technical and management documents, and trade journals, newsletters, and other technical publications provided an additional check on the data.

The objective was to develop a comprehensive list of innovations relating to the installation and long-term performance of stressed-skin panels, originating from both builders and panel manufacturers. Where several builders claimed simultaneous development of an innovation, I was content to attribute it to "builders" in general; the same holds true for duplicative innovation by panel manufacturers. I did not encounter any cases where substantive claims on the development of an innovation were made by both builders and manufacturers.

Presented in this appendix is not only the source of each innovation, but also its functional value, the outcome from its innovation process, and its cost of delay. These characteristics are those most relevent to this research's objective. The functional value is defined by an innovation's technical function within a residential structure and its related benefits compared to the previous best alternative. The outcome from the innovation process is the existence of a manufacturer-commercialized product, or other assessment of its use in residential construction. The cost of delay equals the amount of costs builder-innovators avoid from not waiting for manufacturers to solve identified problems. This "cost of delay" can provide a basis for how the builders consider their alternatives when they innovate themselves to solve problems.

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FUNCTION: Connection of panel to frame

INNOVATION: Air-compression nailgun for panel connection

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of an air-compression nailgun modified to take the 6 to 12 inch nails which are used to connect the insulative panels to the wood framing. The innovation has the advantage of "shooting" the nails a specified distance into the wood, adjustable to different compressions for different types of wood; otherwise, the nails are often hard to drive securely into the framing structure without damaging the panels.

Innovator and Innovation Process: While attaching the insulative stressed-skin panels to large timber-framed structures, the builder developed the innovation described above. The builder-innovator reported that the total time that the innovation took was 8 hours, and the total cost for time and equipment was approximately $380.

Outcome: This innovation is used by the builder-innovator, but by no other builders identified. It is not available from any manufacturer of panels or equipment.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation enabling the connection of the insulative stressed-skin panels to the frame would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling carpentry crews and all service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the size, shape and location of each panel placement; 2) make panel; 3) incorporate attachment device; 4) conduct engineering analyses to ascertain whether attachment is sufficient to carry the load; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Clip connection system

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of clips which hook onto the panels and attach to the frame using 4 inch nails. The innovation has the advantage of attaching the panels to the frame without damaging the panels, and using much smaller nails. In addition, while some degree of thermal bridging occurs when the nails puncture the continuous skin surface, the clips separate the connection of the panel to the frame from the interior core of the panels and thus avoid all thermal bridging.

Innovator and Innovation Process: While attaching the insulative panels to a timber-framed structure, the builder developed the innovation described above while trying to solve problems encountered on the site. The builder-innovator reported that the total time that the innovation took was 12 hours, and the total cost for time and material was approximately $460.

Outcome: This innovation is used by the builder-innovator, but by no other builders identified. It is not supplied commercially by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the

delay for a manufacturer to deliver a panel incorporating the innovation enabling the connection of the panel to the frame would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling carpentry crews and all service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the size, shape and location of each panel placement; 2) make panel; 3) incorporate attachment device; 4) conduct engineering analyses to ascertain whether attachment is sufficient to carry the load; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Peg and hole connection system

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of a hole drilled through the panel and a corresponding hole drilled in the structural framing. A peg exactly fits these hole and hangs the panel from the structural framing. The size and configuration of the peg and its holes vary relative to the bearing area of the panel attachment. The innovation has the advantage of reducing the thermal bridging, which occurs when metal nails pierce the panel, and avoiding the damage to the panel which can occur when the 6 to 12 inch nails are driven through the panels. It may also provide superior long-term performance to reduce buckling, bending, and other motion around the pin connection of the nails.

Innovator and Innovation Process: While attaching the insulative panels to a timber-framed structure, the builder developed the innovation described above to try to solve problems encountered on the site. The builder-innovator reported that the total time that the innovation took was 8 hours, and the total cost for time and material was approximately $290.

Outcome: This innovation is used by the builder-innovator, but by no other builders identified. It is not supplied commercially by panel manufacturers.

<u>Cost of Delay to User if Manufacturer had Innovated:</u> I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation enabling the connection of the panel to the frame would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling carpentry crews and all service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the size, shape and location of each panel placement; 2) make panel; 3) incorporate attachment device; 4) conduct engineering analyses to ascertain whether attachment is sufficient to carry the load; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

FUNCTION: Connection of panel to foundation

INNOVATION: Glued bottomplate for foundation connection

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of glueing and nailing a piece of 2 inch dimensioned lumber to the foundation sill plate or floor decking. The bottom edge of the panels is routed out to accomodate the bottomplate, and additional glue is spread along the interior surface of the hollow. This method has the advantage of fixing the panels securely to the foundation or floor decking; without this connection, the panel might shift outwards as a load is placed upon it.

Innovator and Innovation Process: Faced with the immediate problem of providing a positive connection between the panels and the foundation, builders devised the innovation described above. Builder-innovators reported that the total time that the innovation took was 4 hours, and the total cost for time and materials was approximately $160.

Outcome: This innovation is now widely used by builders in the industry. It is not supplied commercially by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation enabling the connection of the panel to the foundation would be at least 5 workdays. The cost of the delay for the builder would include re-scheduling carpentry crews and all service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 5 day period would be: 1) receive design information on the location of each panel placement on the foundation sill or decking; 2) make panel; 3) incorporate bottomplate and connector to sill or decking; and 4) deliver panel to site. The cost of this 5 day delay for the builder has a value of $280 per workday or $1,400.

FUNCTION: Installation of Heating/Ventilation/Air Conditioning (HVAC) within panel

INNOVATION: Bow chase for ventilation duct

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of a ventilation duct installed within a panel until 12 inches below the top of the panel; the duct is then angled out over the interior face of the panel and enclosed in a bow chase. This method has the advantage of preserving the load-bearing capacity of the top 12 inches of the panel, where it is most critical, while allowing the installation of venting ducts in the panel wall.

Innovator and Innovation Process: Faced with the immediate problem of installing ventilation ductwork in a stressed-skin panel, a builder devised the innovation described above. The builder-innovator reported that the total time that the innovation took was 2 hours, and the total cost for time and material was approximately $80.

Outcome: This innovation is often used by builders using stressed-skin panels. It is not supplied commercially by panel manufacturers.

<u>Cost of Delay to User if Manufacturer had Innovated:</u> I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for installing ventilation ductwork in the panel would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the mechanical service and interior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the location of the ventilation ducts; 2) make panel; 3) create hollow for ductwork; 4) conduct engineering analysis to check that the load-bearing capacity of the panel is intact; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Plastic pipe shaft for ductwork

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of a PVC (polyvinylchloride) or other plastic pipe cut at one end with angled teeth and attached at the end of a hole saw, to act as an extended hole bit. The pipe is left in place as the vent. The advantage of this method is that it minimizes the disturbance to the panel facings while allowing the installation of ventilation ductwork within the panel itself.

Innovator and Innovation Process: To solve immediate problems associated with installing ventilation ductwork in a stressed-skin panel, a builder devised the innovation described above. The builder-innovator reported that the total time the innovation took was one hour, and the total cost for time and material was approximately $40.

Outcome: The innovation is used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for installing ventilation ductwork in the panel would be at least 10 workdays.

The cost of the delay for the builder would include re-scheduling the mechanical service and interior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the location of the ventilation ducts; 2) make panel; 3) create hollow for ductwork; 4) conduct engineering analysis to check that the load-bearing capacity of the panel is intact; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

FUNCTION: Installation of electrical wiring within panel

INNOVATION: Surface-mounted metal conduit for wiring

Nature of Innovation and Advantage over Previous Best Practice: This innovation consists of installing electrical wiring on top of the interior surface of the panel by using rigid metal conduit, which is a hollow metal tube. The advantage of this method is that it avoids all disturbance of the panels themselves, either to the foam-core or to the load-bearing capacity of the facing sheets. It also allows the wiring, switches, and outlets to be placed in any location.

Innovator and Innovation Process: In response to immediate problems encountered in installing electrical wiring in stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was one hour, and the total time and material costs were approximately $45.

Outcome: The innovation is commonly used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

<u>Cost of Delay to User if Manufacturer had Innovated:</u> I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for installing electrical wiring in the panel would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the electricians and interior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the location of the wiring; 2) make panel; 3) create hollow for electrical wiring; 4) conduct engineering analysis to check that the load-bearing capacity of the panel is intact and meets with local electrical code requirements; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Extended depth baseboard for wiring

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of a baseboard which has a cavity behind it wide enough to accomodate wiring. Outlets can be installed directly in the baseboard. The extra depth of the baseboard can be capped with a deep cove molding. The advantage of this method is that it hides the electrical wiring while leaving the stressed-skin panels completely intact. The wiring is also accessible for later changes to the electrical system.

Innovator and Innovation Process: In response to immediate problems encountered in installing electrical wiring in stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 4 hours, and the total time and material costs were approximately $160.

Outcome: The innovation is commonly used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for

installing electrical wiring in the panel would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the electricians and interior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the location of the wiring; 2) make panel; 3) create hollow for electrical wiring; 4) conduct engineering analysis to check that the load-bearing capacity of the panel is intact and meets with local electrical code requirements; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Double bottom plate below panel for wiring

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of two pieces of 2 inch dimensioned lumber which act as a double bottom plate below the panel. The lower bottomplate is cut along the inside edge to act as a wiring chase. The wiring must still be run from this chase to the height required in the wall. The advantage of this method is that it avoids long cuts in either the foam-core or the facing materials of the panel.

Innovator and Innovation Process: In response to immediate problems encountered in installing electrical wiring in stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 2 hours, and the total time and material costs were approximately $75.

Outcome: The innovation is commonly used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for

installing electrical wiring in the panel would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the electricians and interior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the location of the wiring; 2) make panel; 3) create hollow for electrical wiring; 4) conduct engineering analysis to check that the load-bearing capacity of the panel is intact and meets with local electrical code requirements; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Channels routed in foam on-site for wiring

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of creating a cavity within the foam-core of the stressed-skin panel. With EPS (polystyrene) foam-core panels, the foam melts in the presence of heat, so hollows can be created by using a heated or electrically-charged piece of metal pushed through the foam. With urethane-based foam, the foam must be removed using a router or other gouging tool. The wire is then pushed through the hole. The advantage of this method is that it avoids cutting the facing materials of the panel, and the wiring can be installed at any height in the panel.

Innovator and Innovation Process: In response to immediate problems encountered in installing electrical wiring in stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was only 1 hour, and the total time and material costs were approximately $40.

Outcome: The innovation is commonly used by builders using stressed-skin panels. Most panel manufacturers commercially supply pre-formed electrical chases within the panel at set distances from the top or bottom of the panels.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for installing electrical wiring in the panel would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the electricians and interior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the location of the wiring; 2) make panel; 3) create hollow for electrical wiring; 4) conduct engineering analysis to check that the load-bearing capacity of the panel is intact and meets with local electrical code requirements; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

<u>INNOVATION:</u> Door and window openings for wiring

<u>Nature of Innovation and Advantage over Previous Best Practice:</u> The innovation consists of installing electrical wiring within the openings cut for door or window installation. A small hollow sufficient to hold the wire in place is created in the foam after the opening has been cut and the foam routed for the installation of headers and subjambs where necessary, but before the door or window is installed. The wires can then be led further into the walls as necessary by routing holes. The advantage of this method is that the wiring can be installed at switch height with a miniumum of disturbance of the facing materials and foam-core of the panel.

<u>Innovator and Innovation Process:</u> In response to immediate problems encountered in installing electrical wiring in stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was only 1 hour, and the total time and material costs were approximately $40.

<u>Outcome:</u> The innovation is commonly used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for installing electrical wiring in the panel would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the electricians and interior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the location of the wiring; 2) make panel; 3) create hollow for electrical wiring; 4) conduct engineering analysis to check that the load-bearing capacity of the panel is intact and meets with local electrical code requirements; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

<u>INNOVATION:</u> Vertical edges between panels for wiring

<u>Nature of Innovation and Advantage over Previous Best Practice:</u> The innovation consists of using the vertical edges between the panels to install the electrical wiring in a stressed-skin panel. As the panels are erected, the wiring is run up from the basement between the panels in the location and to the height required, within a small hollow in the foam sufficient to hold the wire. The wires can then be led further into the walls as necessary by routing holes. The advantage of this method is that the wiring can be installed at any height with a minimum disturbance to the facing materials and foam-core of the panel.

<u>Innovator and Innovation Process:</u> In response to immediate problems encountered in installing electrical wiring in stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was only 1 hour, and the total time and material costs were approximately $40.

<u>Outcome:</u> The innovation is commonly used by builders using stressed-skin panels. A few panel manufacturer commercially supply panels which have a small hollow adequate for installing electrical wiring along their vertical

edges.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for installing electrical wiring in the panel would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the electricians and interior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the location of the wiring; 2) make panel; 3) create hollow for electrical wiring; 4) conduct engineering analysis to check that the load-bearing capacity of the panel is intact and meets with local electrical code requirements; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Overhead beam for ceiling fixtures

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of cutting the overhead beam to house the electrical wiring for a ceiling fixture. A groove is cut in the top of the beam to the hanging location of the fixture, and then a hole is drilled through the beam. The groove must be covered with a metal plate or some other shield to protect the wiring during subsequent floor nailing. The advantage of this method is that it conceals the wiring for a ceiling-mounted electrical fixture.

Innovator and Innovation Process: In response to immediate problems encountered in installing electrical wiring in stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 4 hours, and the total time and material costs were approximately $145.

Outcome: The innovation is commonly used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for

installing electrical wiring in the panel would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the electricians and interior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the location of the wiring; 2) make panel; 3) create hollow for electrical wiring; 4) conduct engineering analysis to check that the load-bearing capacity of the panel is intact and meets with local electrical code requirements; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

<u>FUNCTION: Connection of panel to roof</u>

<u>INNOVATION:</u> Triangular base for roof connection

<u>Nature of Innovation and Advantage over Previous Best Practice:</u> The innovation consists of cutting a piece of wood at the angle of the roof pitch. This triangular base is attached to the top of the exterior walls to create a strong base and an angled jig for the installation of the roof panels. The triangular base is left in place after erection of the roof. The advantages of this method are the exact positioning of the roof panels, and the increased bearing area of the load of the roof on the triangular base rather than on the single exterior edge of the wall framing.

<u>Innovator and Innovation Process:</u> In response to immediate problems encountered in erecting the stressed-skin panels on the roof and wall framing, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 2 hours, and the total time and material costs were approximately $80.

<u>Outcome:</u> The innovation is commonly used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for installing roof panels on the wall framing in the panel would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the carpenters and all service trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the pitch of the roof and arrangement of panels and wall framing; 2) make panel; 3) create the triangular base; 4) conduct engineering analysis to check that the load-bearing capacity of the panel and the triangular base are adequate for the roof load; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

FUNCTION: Ventilation of roof within panels

INNOVATION: Strapping for the ventilation of roof panels

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of pieces of 2 inch dimensioned lumber placed over the exterior panel surface. These spacers create the necessary air space for ventilation. Plywood decking is then nailed over the spacers. The advantage of this method is the increased air ventilation under the roofing surface, which prevents ice dams, preserves the fire retardancy of the panels, extends the effective lifespan of roofing materials, and reduces heating and cooling loads.

Innovator and Innovation Process: In response to immediate problems encountered in using the stressed-skin roof panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 1 hour, and the total time and material costs were approximately $40.

Outcome: The innovation is commonly used by builders using stressed-skin panels. Two panel manufacturer commercially supply roof panels with molded channels as air ventilation spaces.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for erecting roof panels with a vented airspace would be at least 100 workdays. The cost of the delay for the builder would include re-scheduling the carpenters, roofers, and exterior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 100 day period would be: 1) receive design information on the design of the roof and estimate performance criteria; 2) design panels; 3) perform engineering analysis of panel strength, bending, and other specifications; 4) change panel production system; 5) make panel with vented airspace; 6) conduct independent lab test and gain code approval for new roof panel; and 7) deliver panel to site. The cost of this 100 day delay for the builder has a value of $280 per workday or $28,000.

INNOVATION: Corrugated sheet over roof panel for ventilation

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of a plastic corrugated sheet over the roof panels. Plywood decking can be placed over the sheet, or the roofing material can be laid directly on the sheet. The advantage of this method is that it provides a continuous air ventilation space under the roofing surface, which prevents ice dams, preserves the fire retardancy of the panels, extends the effective lifespan of roofing materials, and reduces heating and cooling loads.

Innovator and Innovation Process: In response to immediate problems encountered in using the stressed-skin roof panels, a builder developed the innovation described above. The builder-innovators reported that the total time the innovation took was 1/2 hour, and the total time and material costs were approximately $23.

Outcome: The innovation is often used by builders using stressed-skin panels. Two panel manufacturer commercially supply roof panels with molded channels as air ventilation spaces.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the

delay for a manufacturer to deliver a panel incorporating the innovation for erecting roof panels with a vented airspace would be at least 100 workdays. The cost of the delay for the builder would include re-scheduling the carpenters, roofers, and exterior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 100 day period would be: 1) receive design information on the design of the roof and estimate performance criteria; 2) design panels; 3) perform engineering analysis of panel strength, bending, and other specifications; 4) change panel production system; 5) make panel with vented airspace; 6) conduct independent lab test and gain code approval for new roof panel; and 7) deliver panel to site. The cost of this 100 day delay for the builder has a value of $280 per workday or $28,000.

FUNCTION: Framing of openings within panel

INNOVATION: Notch in panels for opening framing

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of installing a load-bearing member in the top of a window or door opening by notching the foam core. The advantage of this method is that it allows openings larger than four feet, and the load is distributed away from the opening to the rest of the panel.

Innovator and Innovation Process: In response to immediate problems encountered in framing large openings in stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 1/2 hour, and the total time and material costs were approximately $20.

Outcome: The innovation is commonly used by builders using stressed-skin panels. Several panel manufacturer commercially supply panels with the openings cut and framing installed.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the

delay for a manufacturer to deliver a panel incorporating the innovation for framing openings would be at least 5 workdays. The cost of the delay for the builder would include re-scheduling the carpenters and interior finish crews whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 5 day period would be: 1) receive design information on the size and location of the openings; 2) make the panel; 3) cut the opening and install the framing; and 4) deliver panel to site. The cost of this 5 day delay for the builder has a value of $280 per workday or $1,400.

<u>INNOVATION:</u> Laminated header for opening framing

<u>Nature of Innovation and Advantage over Previous Best Practice:</u> The innovation consists of two pieces of 2 inch dimensioned lumber laminated to a foam core and installed at the top of an opening. The advantage of this method is that it distributes the load away from the opening to the rest of the panel while avoiding any thermal bridging that may occur from solid wood framing.

<u>Innovator and Innovation Process:</u> Two panel manufacturers developed the innovation described above. No information was available on the total time that the innovation took or the total development costs.

<u>Outcome:</u> These two panel manufacturer commercially supply the laminated headers.

FUNCTION: Structural connection between panels

INNOVATION: Single 2 inch dimensioned lumber for panel connection

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of a single piece of 2 inch dimensioned lumber inserted vertically between two panels. The facing sheets are then screwed or nailed to this lumber. The advantage of this method is that it provides a positive structural connection between the adjoining panels, and prevents buckling, bending, and other motion along the connection.

Innovator and Innovation Process: In response to immediate problems encountered in creating a strong connection between adjoining stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 1/2 hour, and the total time and material costs were approximately $20.

Outcome: The innovation is commonly used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the

delay for a manufacturer to deliver a panel incorporating the innovation for a structural connection between panels would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the carpenters and all service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the dimensions of each panel and their connections; 2) conduct engineering analyses to determine the load-bearing capacity of the connection; 3) make the panel; 4) install the connection framing; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Double 2 inch dimensioned lumber for panel connection

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of two pieces of 2 inch dimensioned lumber inserted vertically between the two panels. The two pieces are nailed or screwed together, and the facing sheets are then screwed or nailed to this lumber. The advantage of this method is that it provides a positive structural connection between the adjoining panels to prevents buckling, bending, and other motion along the connection, and it can also act as a post within the panel to carry additional building load.

Innovator and Innovation Process: In response to immediate problems encountered in creating a strong connection between adjoining stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 1 hour, and the total time and material costs were approximately $39.

Outcome: The innovation is commonly used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the

delay for a manufacturer to deliver a panel incorporating the innovation for a structural connection between panels would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the carpenters and all service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the dimensions of each panel and their connections; 2) conduct engineering analyses to determine the load-bearing capacity of the connection; 3) make the panel; 4) install the connection framing; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

<u>FUNCTION: Corner connection between panels</u>

<u>INNOVATION:</u> Open corner connection between panels

<u>Nature of Innovation and Advantage over Previous Best Practice:</u> The innovation consists of drawing back both of the panels from the corner of the foundation, leaving an "open corner". The interior foam corners of the panels are sealed with 2 inch dimensioned lumber of the same depth as the panels, and is boxed in before the exterior sheathing and siding is applied. The advantages of this method are that it provides a solid structural connection between the panels at the corner, and this open corner space can be used to run wiring, plumbing or other services during construction.

<u>Innovator and Innovation Process:</u> In response to immediate problems encountered in creating a strong connection between stressed-skin panels at a corner joint, a builder developed the innovation described above. The builder-innovator reported that the total time the innovation took was 2 hours, and the total time and material costs were approximately $80.

<u>Outcome:</u> The innovation is often used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

<u>Cost of Delay to User if Manufacturer had Innovated:</u> I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for a structural corner connection between panels would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the carpenters and all service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the dimensions of each panel and the angle and location of corner connections; 2) conduct engineering analyses to determine the load-bearing capacity of the corner connection; 3) make the panel; 4) cut the panels to the angle of the corner and install the connection framing; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Extended panel facing for corner connection

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of extending one of the facing sheets of the panel to overlap the depth of the panel meeting at the corner. The advantage of this method is that this corner connection provides a weathertight seal, as well as a positive structural connection between the adjoining panels at the corner to prevent buckling, bending, and other motion along the connection.

Innovator and Innovation Process: In response to immediate problems encountered in creating a strong and tightly sealed connection between stressed-skin panels at a corner joint, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 1 hour, and the total time and material costs were approximately $40.

Outcome: The innovation is commonly used by builders using stressed-skin panels. A few panel manufacturers commercially supply corner panels with extended facings.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the

delay for a manufacturer to deliver a panel incorporating the innovation for a structural corner connection between panels would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the carpenters and all service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the dimensions of each panel and the angle and location of corner connections; 2) conduct engineering analyses to determine the load-bearing capacity of the corner connection; 3) make the panel; 4) cut the panels to the angle of the corner and install the connection framing; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Corner ties for corner connection between panels

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of galvanized metal plates that wrap around the inside and outside of the panel corner. These plates are then screwed to the panel facing, and the exposed foam is covered with additional sheathing or otherwise sealed. The advantage of this method is that this corner connection is a positive structural connection between the adjoining panels at the corner to prevent buckling, bending, and other motion along the connection.

Innovator and Innovation Process: This innovation was developed by a panel manufacturer to create a structural corner connection. No information was available on the the total time the innovation took or the total development costs.

Outcome: The panel manufacturer commercially supplies the corner ties as part of its panel sales.

FUNCTION: Insulated connection between panels

INNOVATION: 2x4 lumber and expanding foam for insulated connection

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of a piece of 2 inch by 4 inch lumber inserted behind and parallel to the facing sheets of the stressed-skin panel. Expanding foam is sprayed around the lumber and over the exposed foam-core and the edges of the lumber, and the facing sheets are screwed to the lumber. The advantage of this method is the foam expands to provide an airtight insulated connection between the panels, avoiding air infiltration and thermal bridging.

Innovator and Innovation Process: In response to immediate problems encountered in creating an insulated and airtight seal between stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 1 hour, and the total time and material costs were approximately $40.

Outcome: The innovation is commonly used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for an insulated and airtight connection between panels would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the carpenters and all service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the dimensions of each panel and the connections; 2) conduct engineering analyses to determine air-infiltration and insulative values for the connections; 3) make the panel; 4) create the airtight seal; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Thin spline for insulated connection

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of 3 inch plywood pieces which are installed behind and parallel to the panel faces. The facing sheets are then screwed to these thin splines. The advantage of this method is that it provides a thermally insulated connection between the panels while allowing the joints to lie flat.

Innovator and Innovation Process: In response to immediate problems encountered in creating an insulated and airtight seal between stressed-skin panels, a builder developed the innovation described above. The builder-innovator reported that the total time the innovation took was 1 hour, and the total time and material costs were approximately $40.

Outcome: The innovation is often used by builders using stressed-skin panels. One panel manufacturer commercially supplies the thin splines.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for an insulated and airtight connection between panels would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the carpenters and all service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the dimensions of each panel and the connections; 2) conduct engineering analyses to determine air-infiltration and insulative values for the connections; 3) make the panel; 4) create the airtight seal; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: In-place foamed spline for insulated connection

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of a spline with three grooves routed into the intersection surface, which provide a space for the beads of expanding foam. The splines are slid into hollows in the foam core, and the foam expands to make the connection. The advantage of this method is that it provides an airtight seal as well as a thermally insulated connection between the panels.

Innovator and Innovation Process: In response to immediate problems encountered in creating an insulated and airtight seal between stressed-skin panels, a builder developed the innovation described above. The builder-innovator reported that the total time the innovation took was 1 hour, and the total time and material costs were approximately $43.

Outcome: The innovation is often used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for an insulated and airtight connection between panels would be at least 10 workdays. The cost of the delay for the builder would include re-scheduling the carpenters and all service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 10 day period would be: 1) receive design information on the dimensions of each panel and the connections; 2) conduct engineering analyses to determine air-infiltration and insulative values for the connections; 3) make the panel; 4) create the airtight seal; and 5) deliver panel to site. The cost of this 10 day delay for the builder has a value of $280 per workday or $2,800.

INNOVATION: Laminated spline for insulated connection

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of two pieces of 2 inch dimensioned lumber laminated to a foam core, which are installed between the panels. The advantage of this method is that it provides a thermally broken connection between the panels, to avoid thermal bridging.

Innovator and Innovation Process: Two panel manufacturer developed this innovation to create an insulated connection between the panels. Information was not available on the total time the innovation took or the total development costs.

Outcome: The two panel manufacturers commercially supply the laminated splines.

INNOVATION: Rolled steel joint for insulated connection

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of a roll-formed steel joint, with edges attached with ring-shank nails, self-tapping screws, and gaskets for the air seal. The advantage of this method is that it uses a mechanical fastening to connect the panel facings, while the foam cores are undisturbed.

Innovator and Innovation Process: A panel manufacturer developed this innovation to create an insulated connection between the panels. Information was not available on the total time the innovation took or the total development costs.

Outcome: The panel manufacturer commercially supplies the panels with the rolled steel joint imbedded in them.

INNOVATION: Cam-lock insulated connection

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of a cam-lock system built directly into the panel. The cam-lock is a hooked piece of metal which moves over an imbedded bar. The lock is engaged by turning the hook with a hex wrench. The advantage of this method is that it uses a mechanical fastening to connect the panel facings, while the foam cores are undisturbed.

Innovator and Innovation Process: Two panel manufacturers developed this innovation to create an insulated connection between the panels. Information was not available on the total time the innovation took or the total development costs.

Outcome: The two panel manufacturers commercially supply panels with the cam-lock imbedded in them.

FUNCTION: Rendering panel insect repellent

INNOVATION: PVC-covered panel for insect repellent

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of a sheet of PVC (polyvinylchloride) or other plastic glued to the exterior of the panels, especially over any exposed foam edges. The advantage of this method is that it provides an insect-proof shield for the panels as well as watertight seal.

Innovator and Innovation Process: In response to immediate problems encountered by infestation by carpenter ants, termites, and other insects in foam-core stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 1 hour, and the total time and material costs were approximately $40.

Outcome: The innovation is often used by builders using stressed-skin panels. A few panel manufacturers commercially supply the PVC-covered panels, though not necessarily for insect infestation.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the

delay for a manufacturer to deliver a panel incorporating the innovation for insect repellent would be at least 250 workdays. The cost of the delay for the builder would include re-scheduling all the structural, finish, and service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 250 day period would be: 1) estimate performance criteria of the insecticide in foam or facing sheets and effect on panel performance; 2) design panels; 3) perform engineering analysis of foam chemical stability, fire retardancy, and structural stability, as well as resulting panel strength and other specifications; 4) test new types of insecticides or foams for repelling on insects; 5) locate new supplier or make new foam compound; 6) change panel production system; 7) make panel; 8) conduct independent laboratory tests to gain code approval for foam changes and potential health effects; and 9) deliver the panel to site. The cost of this 250 day delay for the builder has a value of $280 per workday or $70,000.

INNOVATION: Sprayed on insecticide

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of soaking the panels and the surrounding grounds with insecticide, especially over any exposed foam edges. The advantage of this method is that it may prevent insect infestations for the whole area treated without changing the panels themselves.

Innovator and Innovation Process: In response to immediate problems encountered by infestation by carpenter ants, termites, and other insects in foam-core stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 2 hour, and the total time and material costs were approximately $170.

Outcome: The innovation is commonly used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for insect repellent would be at least 250 workdays. The cost of the delay for the builder would include re-scheduling all the structural, finish, and service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 250 day period would be: 1) estimate performance criteria of the insecticide in foam or facing sheets and effect on panel performance; 2) design panels; 3) perform engineering analysis of foam chemical stability, fire retardancy, and structural stability, as well as resulting panel strength and other specifications; 4) test new types of insecticides or foams for repelling on insects; 5) locate new supplier or make new foam compound; 6) change panel production system; 7) make panel; 8) conduct independent laboratory tests to gain code approval for foam changes and potential health effects; and 9) deliver the panel to site. The cost of this 250 day delay for the builder has a value of $280 per workday or $70,000.

INNOVATION: Site preparation for insect repellent

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of preparing the site itself to decrease the opportunity for insect infestation. The preparation includes clearing the area of wood, cutting back plants and overhanging branches from the structure, and installing specific plants known to be unattractive and even repellent to the insects, such as Tansy. The advantage of this method is that it may prevent insect infestations for the whole area without the health hazards of insecticide spraying and without changing the panels themselves.

Innovator and Innovation Process: In response to immediate problems encountered by infestation by carpenter ants, termites, and other insects in foam-core stressed-skin panels, builders developed the innovation described above. The builder-innovators reported that the total time the innovation took was 4 hour, and the total time and material costs were approximately $160.

Outcome: The innovation is commonly used by builders using stressed-skin panels. It is not commercially supplied by panel manufacturers.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for insect repellent would be at least 250 workdays. The cost of the delay for the builder would include re-scheduling all the structural, finish, and service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 250 day period would be: 1) estimate performance criteria of the insecticide in foam or facing sheets and effect on panel performance; 2) design panels; 3) perform engineering analysis of foam chemical stability, fire retardancy, and structural stability, as well as resulting panel strength and other specifications; 4) test new types of insecticides or foams for repelling on insects; 5) locate new supplier or make new foam compound; 6) change panel production system; 7) make panel; 8) conduct independent laboratory tests to gain code approval for foam changes and potential health effects; and 9) deliver the panel to site. The cost of this 250 day delay for the builder has a value of $280 per workday or $70,000.

INNOVATION: Insecticide in foam

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of an additive to the foam itself which acts as an insect repellent or even an insecticide. The advantage of this method is that it does not require any changes in the building design or grounds, and may last as long as the foam itself.

Innovator and Innovation Process: Several panel manufacturers developed the innovation described above in response to immediate problems encountered by infestation by carpenter ants, termites, and other insects in foam-core stressed-skin panels. No information was available on the total time the innovation took or the total development costs.

Outcome: These panel manufacturers commercially supply panels with the insecticide in the foam.

FUNCTION: Development of curved panel for special design

INNOVATION: Curved panel

Nature of Innovation and Advantage over Previous Best Practice: The innovation consists of curving the facing sheets and the foam to the desired radius for the design. The advantage of this method is that it allows greater design freedom with the panels than is possible with simple straight panels, and the curvature of the panel can range from slight to moderate.

Innovator and Innovation Process: In response to immediate problems encountered by a curved stressed-skin panel section, a builder developed the innovation described above. The builder-innovator reported that the total time the innovation took was 40 hours, and the total time and material costs were approximately $1,500.

Outcome: The innovation is used by a few builders using stressed-skin panels. One panel manufacturer commercially supplies curved panels.

Cost of Delay to User if Manufacturer had Innovated: I calculate that the delay for a manufacturer to deliver a panel incorporating the innovation for

this special design feature would be at least 100 workdays. The cost of the delay for the builder would include re-scheduling all the structural, finish, and service installation trades whose work depends upon the completion of this task. The steps the manufacturer would have to take during this 100 day period would be: 1) estimate performance criteria of the curved panel; 2) receive design information about the curvature required; 3) design panels; 4) perform engineering analysis to determine the structural stability, buckling strength and other specifications; 5) change panel production system; 6) make panel; 7) conduct independent laboratory tests to gain code approval for panel changes; and 8) deliver the panel to site. The cost of this 100 day delay for the builder has a value of $280 per workday or $28,000.

Appendix B: Innovations Permanently Installed in Residential Structures and Commercialized in the U.S., 1945 to 1990

B. 1 Introduction

This sample contains innovations which are permanently installed in residential structures. All of these innovations were commercially introduced after the end of World War II. This sample is a subset of all innovations which have appeared in the residential construction industry, but it can provide a general overview of the character of innovations in this industry. Chapter 2 describes the residential construction industry relative to the development and use of innovations.

I constructed this sample through a comprehensive survey of the literature. Chapter 4 explains the methodology for the data collection. It was checked for accuracy and validity through a complete review by several experts in residential construction, and they judged it complete and accurate.

The objective of this sample was to provide a general context for a more detailed analysis of the process of innovation in residential construction. Each of the 117 identified innovations were examined for its technical function within a residential building and its related costs and benefits compared to the previous best alternative. The description of each innovation also includes a note on whether the innovation is supplied commercially by manufacturers.

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Functional Area: Structural Exterior Wall

Structural Panel

The innovation consists of 2x4 studs attached to a structural facing material, such as plywood or asbestos sheets. The studs act as ribs to transfer the building load to the skins and to stiffen the panel. Its advantages are the potential for pre-fabrication and reduction of the number of wood studs required. It is commercially supplied by manufacturers.

Stressed-Skin Panel

The innovation consists of a sandwich of a solid core of plastic insulative foam laminated to facing materials, where the facing material carry some portion of the building load. The panel acts similarly to an I-beam to distribute the load. The facing materials can be made from plywood, other structural wood sheets, gypsum board, or metal. Its advantages are the potential for prefabrication, the elimination of wood studs, and the elimination of the separate step of installaing insulation. It is commercially supplied by manufacturers.

Two Stud Corner

The innovation consists of the elimination of the standard third stud, which serves primarily to back up interior finish material. It requires the additional use of wood structural panels to produce adequate load-bearing capacity. Its advantage is the reduction of the number of wood studs required. (U.S. Department of Housing and Urban Development, 1988b; Ventre, 1973). This innovation is not commercially supplied by manufacturers.

2x6 Framing Members

The innovation consists of framing members which are two inches deeper than normal framing (i.e. 2x6 as compared to 2x4). Its advantages are that it allows extra wall cavity for increased insulation, thereby increasing the energy efficiency of a structure while limiting the labor costs. It also allows additional room for service installation (Wilson, 1988). It is not commercially supplied by manufacturers.

24 Inch On-Center Wall Framing

The innovation is the spacing of wood studs 24 inches apart, which is an increase of the standard framing space between studs of 16 inches on-center. Its advantage is the reduction of the regular studding material and labor by nearly one third (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

Single Top Plate

The innovation is a single top plate at the top of a framed wall, rather than the standard framing of a double top plate. It can be used when studs and trusses are in line. Its advantage is the elimination of one third of the plate material required (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

Elimination of Wall Blocking

The innovation is the elimination of pieces of wood ("blocking") placed horizontally between the studs to act as a fire-break. This blocking can be eliminated because wall plates, floor sheathing, and insulation provide sufficient constriction of airflow within the wall to minimize fire spread, as long as the structure is platform framed, and not balloon-framed (U.S. Department of Housing and Urban Development, 1988b). Its advantage is the reduction in time and material required for the blocking. It is not commercially supplied by manufacturers.

Functional Area: Enclosure and Insulation

Structural Composite Wood as Sheathing

The innovation is wood panels (such as plywood, oriented strand board, or particleboard) constructed from laminated veneers and reconstituted wood pulp. Its advantage is the significant rigidity it adds to a framed structure through application as sheathing, allowing wider spacing of studs (Furlong and Nutt-Powell, 1979). It is commercially supplied by manufacturers.

Air/Vapor Barrier

The innovation consists of a continuous membrane, sealed at seams and penetrations, placed under the interior wall surface. The plastic sheet is usually a polyethylene sheet which is stapled to the interior frame. Its advantage is the reduction or elimination of moisture transported by convection by erecting an impermeable barrier on the warm side of an insulated surface (Nisson, 1988). It is commercially supplied by manufacturers.

Airtight Drywall Approach

The innovation consists of gypsum board, gaskets and sealants assembled to function as an air/vapor barrier system. Its advantages are a barrier to air infiltration while allowing a certain degree of moisture exchange, thereby decreasing the potential for moisture condensation problems within the wall cavities (Nisson, 1988). It is not commercially supplied by manufacturers.

Exterior Foam Sheathing

The innovation consists of sheets of rigid insulative foam installed on the exterior of the framing to create a continuous exterior insulative and sheathing surface. Because it does not have the shear strength of wood structural sheets, 16 inch on center stud spacing is recommended, and it may entail moisture and condensation problems from a cold-side vapor retarder. Its advantages are the elimination of the wood exterior sheathing and some interior insulation (Nisson, 1988). It is commercially supplied by manufacturers.

Reflective Paint

Reflective paint consists of a coating applied to either the interior or exterior roof surfaces that reflects solar gain. Its advantages are the reduction of heat loss and gain in buildings (Energy Design Update, Nov. 1988). It is commercially supplied by manufacturers.

Reflective Foil

The innovation is a thin reinforced reflective foil, or a reflective surface on a rigid boardstock. The reflective face should abutt an air space of two inches. Its advantage is the reduction of summer heat gain (Energy Design Update, Nov. 1988; Degelman and Snider, 1989). It is commercially supplied by manufacturers.

Aluminum/Vinyl Siding

The innovation consists of pieces of aluminum or vinyl pre-formed to resemble lap wood siding, and used as exterior siding. The upper and lower edges interlock for connection with successive courses. Its advantage is its longevity as an exterior finish material. It is commercially supplied by manufacturers.

Sprayed Concrete/Stucco

The innovation is a lightweight concrete, applied to a building face with large sprayers, and finished to look like stucco, "fieldstone", or bricks. Its advantages are its longevity as an exterior finish surface, and a minor insulative value. It is commercially supplied by manufacturers.

Functional Area: Openings

Double-Glazed Window

The innovation consists of two pieces of glass with an airspace between them. Its advantages are the reduction in the heat loss through the window and the decrease in air infiltration. It is commercially supplied by manufacturers.

Triple-Glazed Window

The innovation consists of either a film suspended in the air space between two panes of glass or a third sheet of glass. Its advantages are a lower emissivity (radiation of heat) of the windows and a reduction in heat loss and air infiltration. It is commercially supplied by manufacturers.

Low-Emissivity Coated Window

The innovation consists of a coat of film applied to the glass surfaces, preferably the interior surfaces of a double-paned sash. Its advantage is the reduction the surface emissivity of heat through the glass. It is commercially supplied by manufacturers.

honeycomb. The edges are solid wood to accomodate hinges and locks. Its advantage is the significant reduction in weight. It is commercially supplied by manufacturers.

Insulated Exterior Door

The innovation consists of a door with a core of plastic insulative foam or other insulating material. Its advantages are the increased insulative value and decreased air infiltration around and through the door (Dietz, 1974). It is commercially supplied by manufacturers.

Aluminum/Vinyl Coated Trim

The innovation consists of coating sashes and trim with either aluminum or vinyl. Its advantage is its longevity as an exterior finish material. It is commercially supplied by manufacturers.

Weatherstripping

The innovation consists of strips of flexible plastics installed around the edges of door and windows openings. Its advantage is the reduction of air infiltration, thereby reducing the heating load of a building. It is commercially supplied by manufacturers.

Caulk/Sealant

The innovation consists of adhesive or expanding caulk and sealant placed around all openings, and all penetrations in the skin (such as wire or pipe holes). Its advantage is the significant reduction of air infiltration. It is commercially supplied by manufacturers.

Elimination of Header and Jack Stud

The innovation is the elimination of the header and jack studs, which are required only where loads must be carried to the sides of the window or door openings. These members can be eliminated if the loads are absent, or if other members (sheathing, trusses, joists) carry the load. Its advantage is the reduction of material and labor required for framing (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

Box Header

The innovation replaces a single or double 2x8 header with a glue-nailed plywood box header. Its advantages are lower material and labor costs, an extra space for insulation, and considerably less cross-grain shrinkage (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

Functional Area: Interior Wall Framing

Solid Drywall Partition

The innovation consists of face panels of 1/2 inch or 5/8 inch laminated to a 1 inch drywall core, resting on a wood or metal track for stabilization. While it is more expensive than a wood framed wall and not as rigid, its advantage is the reduction of time and material to construct the interior wall (Emerson and Olesky, 1983). It is commercially supplied by manufacturers.

Drywall Clips

The innovation consists of clips which attach at the edges of the gypsumboard surface. They are particularly used at corners and intersections. Its advantage is the reduction of framing through the elimination of extra nailing surfaces (Emerson and Olesky, 1983). It is commercially supplied by manufacturers.

Partition Connector at Truss

The innovation consists of a special plate nailed to the top of a framed interior wall with a movable nail in the connector. Its advantage is that it allows the truss to move without breaking the connection (Journal of Light

Construction, May 1990, p. 65). It is commercially supplied by manufacturers.

Steel Studs

The innovation is the replacement of wood studs with steel tubes. Its advantages are additional fire protection, and decreased labor time, but it does increase material costs (Emerson and Olesky, 1983; U.S. Department of Housing and Urban Development, 1988b). It is commercially supplied by manufacturers.

24 Inch On-Center Interior Wall Framing

The innovations is increasing the stud spacing to 24 inches on-center from the standard spacing of 16 inches. Its advantage is the reduction by nearly one third of regular studding material and labor (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

2x3 Framing

The innovation is the use of thinner framing studs (3 inches thick rather than 4 inches). Its advantages are the addition of interior square footage without sacrificing partition performance. The thinner walls, however, will not accomodate most plumbing sizes, electrical boxes and ductwork (Emerson and Olesky, 1983). It is not commercially supplied by manufacturers.

Elimination of Partition Post

The innovation is the elimination of the full height 2x4 member by nailing the partition to a mid-height wall block. Its advantage is the reduction of framing material and labor (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

Functional Area: Foundation

All Wood Foundation

The innovation consists of pressure-treated studs and structural wood sheets assembled as an underground foundation. Its advantages are the potential for off-site panelization, faster completion time, and a better thermal rating, since the wood framing has a higher insulative value than concrete and it allows extra space for the installation of interior insulation (Labs et al., 1988; Nisson, 1988). It is not commercially supplied by manufacturers.

Combination Insulation/Concrete Form

The innovation is a combination of insulation and concrete in-place pouring form usually made from polystyrene blocks; it functions as both the form for a cast-in-place foundation and as the permanent insulation (interior and exterior). While the forms aren't as well braced as wood forms so the concrete must be poured more slowly, its advantages are that the insulating qualities allow pouring at lower temperatures, and the innovation eliminates the extra steps of stripping the foundation form prior to the application of insulation (Fine HomeBuilding, June/July 1987, p. 86). It is commercially supplied by manufacturers.

Rigid Foam Insulation

The innovation consists of sheets of plastic insulative foam glued to the exterior or interior of the foundation. Its advantages is the reduction of heat loss through the foundation wall (Labs et al., 1988). It is commercially supplied by manufacturers.

Shallow Horizontal Foam

The innovation is a piece of rigid foam insulation installed 12 inches deep near the foundations, and sloped to 20 inches deep at the outer edge, extending at least 3 feet from the foundation wall. The advantage of this method is that it retards the flow of heat from the foundation to the ground surface but not to the deep earth (where there is a constant temperature of around 50 degrees) (Nisson, 1988; Labs et al., 1988). It is commercially supplied by manufacturers.

Waterproofing

The innovation consists of a light asphalt emulsion, covered by a plastic vapor barrier. The covering materials must be strong and tough and flexible enough to accomodate foundation cracking. Its advantage is the elimination of water infiltration through cracks in the foundation (Emerson and Olesky, 1983). It is commercially supplied by manufacturers.

Lightweight Insulated Concrete

The innovation consists of masonry blocks made with polystyrene beads instead of aggregate in the concrete mixture. Its advantage is significant higher R-values than standard concrete blocks (Labs et al., 1988). It is commercially supplied by manufacturers.

Rigid Foam within Cast-in-Place Foundation

The innovation consists of suspending a sheet of plastic insulative foam within the form for a cast-in-place foundation before the concrete is poured. Its advantage is the provision of a continuous, evenly-distributed layer of insulation within the wall, eliminating convective heat transfer (Labs et al., 1988). It is commercially supplied by manufacturers.

Granular Insulation within Wall Cavities

The innovation consists of pouring polystyrene beads or granular insulation materials into the cavities of conventional masonry walls. Its advantage is the elimination of convective heat loss through the hollow cores of the blocks (Labs et al., 1988). It is commercially supplied by manufacturers.

Foam Insulation within Cavities

The innovation consists of inserting blocks of rigid insulating foam within the cores of concrete blocks. Its advantage is the elimination of convective heat loss through the hollows (Labs et al., 1988). It is commercially supplied by manufacturers.

Air/Vapor Barrier under Slab or Crawl Space

The innovation is the installation of a sheet of plastic to act as a continuous membrane under a poured slab or over the ground in a foundation crawl space. Its advantages are the reduction of moisture transport through convection, and of risks from radon gases. It is commercially supplied by manufacturers.

Foundation Sill Sealer

The innovation is a glass fiber sealer placed between the sill plate and the foundation wall. Its advantages are the reduction of air infiltration and the addition of a levelled surface for the rough top surface of the foundation (Johnson, 1981). It is commercially supplied by manufacturers.

Rim/Band Insulation

The innovation is a strip of rigid foam insulation installed on the exterior or interior of the rim joist or band or header that rests directly on the sill, and encircles the periphery of the building. This innovation minimizes thermal bridging, and external application practically eliminates the potential for condensation (Labs et al., 1988). It is commercially supplied by manufacturers.

Functional Area: Floor Framing

Open Web Floor Truss

The innovation is two pieces of 2 inch by 4 inch wood lengths connected by web members, also made from 2x4s. The joints are connected using metal plates. Its advantages are that it can span longer distances with less wood than standard floor joists, and the open web allows easy installation of services (Koel, 1985; Lytle and Reschke, 1982; Emerson and Olesky, 1983; U.S. Department of Housing and Urban Development, 1988b). It is commercially supplied by manufacturers.

I-Beam Floor Truss

The innovation is two pieces of 2 inch by 4 inch lumber laminated to a solid structural wood web, such as plywood or oriented strand board. Its advantage is a longer span than is possible using wood joists (Koel, 1985; Lytle and Reschke, 1982; Emerson and Olesky, 1983; U.S. Department of Housing and Urban Development, 1988b). It is commercially supplied by manufacturers.

Built-up Wood Beams

The innovation consists of wood pulp and veneer laminated to form a solid beam. Its advantage are a span equivalent to that of a similarly sized steel beam, at a lower cost (U.S. Department of Housing and Urban Development, 1988b). It is commercially supplied by manufacturers.

Gluenailed Subfloor

The innovation consists of glue-nailing a plywood subfloor to the floor framing. Its advantages are the reduction in the size/number of framing members required, by altering the floor framing to act as a composite T-beam, and it also reduces floor squeaks and stiffens the floor (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

24 Inch On-Center Joist Framing

The innovations consists of spacing the floor joists 24 inches apart, rather than the 16 inches in standard framing. Its advantage is the reduction by up to one third of standard labor and materials over 16 inch framing (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

Elimination of Joist Blocking

The innovation consists of eliminating the bridging or blocking between floor joists used in standard framing, which is not needed with current kiln-dried lumber. Its advantage is significant savings in material and labor (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

Elimination of Double Joists

The innovation consists of eliminating double floor joists used in standard framing, which are not necessary under nonload-bearing interior partitions. Its advantage is savings in lumber costs (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

Off-Center Spliced Joists

The innovation consists of splicing two joists of unequal length together off the center of the span, rather than the conventional method of overlapping two joists over the center girder. Its advantages are the simplification of subfloor layout, the reduction of lumber requirements, and improved structural capacities (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

Foundation Anchors

The innovation consists of imbedding metal anchor straps in the foundation, which are then wrapped around and nailed to the sill plate and joists. Its advantages are the resistance of wind forces acting on the structure, while eliminating the holes in the sill for the bolts and the interference with the joist framing required for standard anchoring techniques (U.S. Department of Housing and Urban Development, 1988b). It is commercially supplied by manufacturers.

Plates and Hangers

The innovation consists of lightweight metal connectors which replace joist notching, or angled nailing ("toe-nailing"). Its advantage is significantly superior structural capacity (Berg, 1988; Loeffler, 1989). It is commercially supplied by manufacturers.

Functional Area: Roof Framing

Insulated Roof Panel

The innovation consists of a panel filled with insulative plastic foam laminated to structural plywood (or the equivalent) on both sides, or with the interior face covered in finish material. Its advantages can include the reduction in the number of required framing members or trusses, and increased load-bearing capacity. It is commercially supplied by manufacturers.

Roof Truss

The innovation consists of framing members (2 inch by 4 inch up to 2 inch by 10 inch), fastened together with steel plate connectors. Its advantages are the ability to span the depth of a house without intermediate support, and decreased material and labor costs over standard rafter framing (Emerson and Olesky, 1983; Ventre, 1973). It is commercially supplied by manufacturers.

Air/Vapor Barrier

The innovation consists of a sheet of plastic stapled to the interior roof framing which acts as a continuous membrane on the warm side of an insulated surface. Its advantage is the elimination of moisture transport by convection, thereby decreasing the heating load of a building (Nisson, 1988). It is commercially supplied by manufacturers.

Roof Ventilation System

The innovation consists of either active fan-based systems that expel air from attics and roof spaces, or passive elements that allow air movement under the roofing materials. Its advantages are the avoidance of moisture condensation and ice-build-up, and the increased effective lifespan of the roofing materials. The venting may also remove excess heat during hot weather (Nisson, 1988). It is commercially supplied by manufacturers.

24 Inch On-Center Rafter Framing

The innovation consists of spacing the rafters 24 inches apart, rather than the 16 inches used in standard framing. Its advantage is the reduction by one third the amount of materials and labor used for 16 inch rafter spacing (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

Plywood Sheathing Clips

The innovation is clips that connect large plywood panels structurally to each other. Its advantage is the elimination of the alignment of the connection between the plywood sheets to the roof framing, thereby simplifying the framing and sheathing (Dietz, 1974). It is commercially supplied by manufacturers.

Plates and Hangers

The innovation consists of lightweight metal connectors which replace joist notching, or angled nailing ("toe-nailing"). Its advantage is significant superior structural capacity compared to standard framing (Berg, 1988; Loeffler, 1989). It is commercially supplied by manufacturers.

Functional Area: Roof Covering

Rubber Roofing

The innovation consists of large sheets of EPDM (ethylene propylene diene monomer) rubber that are sealed at all joints. Its advantage is the creation of a continuous waterproof membrane over flat or slight pitch roofs. It is commercially supplied by manufacturers.

Modified Bitumen Roofing

The innovation consists of basic bitumen (a by-product of oil or coal refining) with specific chemicals added to improve its performance in terms of pliability and stability. The three major types of application are hot-mopping, self-adhering and torch-applied. Its advantages are that it is easily repaired, quickly applied, and lasts longer than other materials (Rose, 1988). It is commercially supplied by manufacturers.

Copper-clad Shingle

The innovation consists of a thin coating of copper over a flexible modified asphalt (bitumen), fiberglass, or silicone sand base. Its advantages are that it is more flexible and less expensive than a standing-seam copper roof (O'Brien, May 1988). It is commercially supplied by manufacturers.

Cement Shingle/Tile

The innovation consists of a mixture of cement and other additives, such as fiberglass and other mineral fibers. Its advantages are that it can mimic the look of slate, wood, and tiles, and, because of the fiber-reinforcing, there are some claims that it lasts longer than other tiles (O'Brien, May 1988; Koel, 1985). It is commercially supplied by manufacturers.

Fiberglass Shingle

The innovation consists of a fiberglass mat covered with asphalt and mineral granules. Its advantages are that it imitates the appearance of wood or slate, it is a durable surface, and it has an increased fire-rating over other roofing materials; it can also include a self-laminating strip that eliminates the stage of sealing the first course and that increases wind resistance (Koel, 1985; O'Brien, May 1988). It is commercially supplied by manufacturers.

Structural Wood Sheathing Panel

The innovation consists of wood panels constructed from laminated veneers and reconstituted wood pulp. Its advantage is its significant rigidity, which can allow the reduction of framing lumber. It is commercially supplied by manufacturers.

Roughened OSB

The innovation consists of Oriented Strand Board (OSB), a composite wood panel used for roof sheathing, with a special roughened exterior surface used for roof sheathing. Its advantage is increased safety for roof work. It is commercially supplied by manufacturers.

Functional Area: Plumbing

Wet Wall/Core

The innovation is the concentration of all plumbing within a small central core. Its advantages are that it decreases the length of pipes that have to be run and it allows the potential for off-site fabrication (U.S. Department of Housing and Urban Development, 1988b; Lytle and Reschke, 1982). It is commercially supplied by manufacturers.

Fiberglass Shower/Bath

The innovation is a continuous piece of molded fiberglass that encompasses the shower walls and bathtub. Its advantages are decreased labor and material costs compared to tiling. It is commercially supplied by manufacturers.

Wall-hung Toilet

The innovation is a toilet hung from the wall rather than resting on a pedestal. Its advantages are simplified plumbing arrangement and easier maintenance and cleaning. It is commercially supplied by manufacturers.

Watersaving Toilet

The innovation is a toilet that has a smaller tank or shallower bowl than standard toilets. Its advantage is the reduction by over one half of the amount of water used in standard toilets. It is commercially supplied by manufacturers.

Tankless Hot Water Heater

The innovation consists of a heated coil to warm the water as it passes through. While the volume outtake on these heaters is lower than normal tank water heaters, its advantage is a significant reduction in energy costs. It is commercially supplied by manufacturers.

Solar Powered Water Heater

The innovation uses solar panels to heat the water as it passes across the panel material, which is then stored in a tank until use. Its advantage is significantly reduced energy costs. It is commercially supplied by manufacturers.

Plastic Pipes for Waste

The innovation is a pipe made of polyvinyl chloride (PVC) or acrylonitrile-butadiene-styrene (ABS) used for outgoing water flow (drain and waste) or as venting. Its advantages are that it is lighter and less expensive than copper and cast iron pipes (Ventre, 1973). It is commercially supplied by manufacturers.

Plastic Pipe for Supply

The innovation is a pipe made from CPVC (chloro-polyvinyl chloride) or poly-butelyne (PB). The CPVC pipe is rigid and lightweight, while the PB pipe is flexible. Its advantages are that it is lighter and less expensive than copper pipes, and the flexible PB pipe can decrease labor time for plumbing installation (U.S. Department of Housing and Urban Development, 1981b; U.S. Department of Housing and Urban Development, 1988b). It is commercially supplied by manufacturers.

Thin-walled Copper Pipe

The innovation consists of a copper pipe with an extra-thin wall. Its advantages are increased ease of installation and reduction of the use of lead solder (Ventre, 1973; U.S. Department of Housing and Urban Development, 1981b). It is commercially supplied by manufacturers.

Insulated Water Pipe

The innovation consists of a water pipe with an extra insulating layer, used for the runs from the hot water heater to appliances and fixtures. Its advantage is significant reduction in energy use by reducing the amount of heat lost from hot water pipes. It is commercially supplied by manufacturers.

Plumbing Tree

The innovation is the assemblage of plastic waste pipes into a "tree". Its advantages are the potential for off-site fabrication for standard plumbing configurations and decreased labor costs (Ventre, 1973). It is commercially available from manufacturers.

Single Stack Vent/Drain

The innovation consists of a single ventilation and drainage stack which is capable of handling the same loads (in 3 story buildings) as the conventional system of separate vents and drains for each floor and fixture. Its advantages are the elimination of duplicate systems, and the accompanying savings in materials, labor, and plumbing space within the building (Ventre, 1973; U.S. Department of Housing and Urban Development, 1988). It is not commercially supplied by manufacturers.

Functional Area: Electrical Wiring

"Integrated" Wiring

The innovation consists of electrical wiring which also carries the signals to control certain appliances, fixtures, and other systems. Its advantages are that it uses the residential wiring system as an integrated unit, it limits the number of wires carrying electrical pulses, and it allows non-site control of appliances and electrical machinery (O'Brien, December 1988). It is commercially supplied by manufacturers.

Nonmetallic Sheathed Cable

This innovation consists of 2 to 4 individually insulated conductors with an insulated ground wire, wrapped in a fibre core, and enclosed in a sheath of plastic. Its advantages are that it is lighter, more flexible, less expensive, and easier to install than armored cable and rigid conduit (Ventre, 1973). It is commercially supplied by manufacturers.

Plastic Outlet Box

The innovation is a molded plastic box to hold the electrical outlet. Its advantages are that it is less expensive than standard metal boxes, and it conducts less heat so can easily be integrated into energy efficient and "tight" houses (U.S. Department of Housing and Urban Development, 1988b). It is commercially supplied by manufacturers.

Surface Mounted Outlet

The innovation consists of a shallow electrical outlet box which is attached to the interior wall surface rather than the wall framing. Its advantage is that it allows a continuous vapor barrier to remain unpenetrated. It is commercially supplied by manufacturers.

Functional Area: Heating/Ventilation/Air Conditioning

Imbedded Radiant Heat

The innovation consists of a heat source distributed under a floor or ceiling surface. For a ceiling system, the radiant heating units are electrical conducting sheets that are covered with sheetrock. The underfloor system are electrical cables or tubes filled with a liquid, usually imbedded in a concrete subfloor for stability and heat retension, with a finish floor surface placed above. Its advantages are the evenness of the heat distribution, the increased comfort of the inhabitants, and effectivenees for "zone heating" configurations (Adelman, 1984). It is commercially supplied by manufacturers.

Air-to-Air Heat Exchanger

The innovation consists of an exchanger unit which transfers heat from exhaust air to fresh incoming air. Its advantages are that it provides circulating fresh air while reducing heating loads (Nisson, 1988). It is commercially supplied by manufacturers.

Heat Pump

The innovation consists of an air ventilation system which withdraws heat from the air in one location and pumps it towards another; for example, in the summer it can pump warm indoor air outside, and in the winter it can take heat from the outside air and pump it indoors, as well as reclaiming heat from exhausted inside air. Its advantages are that it provides circulating fresh air, it generates greater savings than an air-to-air heat exchanger because heat is recovered year round, and it can be incorporated into an air-conditioning system to reduce cooling costs (Nisson, 1988). It is commercially supplied by manufacturers.

Combination Furnace/Hot Water Heater

The innovation consists of a heating element which heats hot water for use in both radiators and plumbing fixtures. Its advantages are the reduction in water heating costs and the elimination of duplicative water heating and supply systems (Energy Design Update, 1988). It is commercially supplied by manufacturers.

Condensing Furnace

The innovation consists of a furnace which increases the air pressure in the combustion chamber. Its advantage is increased energy efficiency, thereby lowering fuel costs. It is commercially supplied by manufacturers.

Humidifier and Dehumidifier

The innovation consist of units which either supply moisture to the heated air (humidifier) or extract moisture from the heated air (dehumidifier). Its advantages are that, since the amount of moisture in the air influences the amount of heat required, it can reduce heating costs and improve the comfort of the inhabitants. It is commercially supplied by manufacturers.

Mechanical Bathroom Ventilation

The innovation consists of a metal sleeve with an electrical exhaust fan and built-in external damper placed in a bathroom ceiling or exterior wall. Its advantage is that it provides ventilation upon demand and so eliminates the need for a window (Ventre, 1973). It is commercially supplied by manufacturers.

Thermostatic Control

The innovation consists of an electrical switch to control the activitation of the furnace, as well as a thermometer and a dial to select the temperature, and a timer to set building warm-up periods before habitation. Its advantages are decreased fuel costs, and increased resident comfort from automatic furnace start-up to maintain a regular in-door temperature. It is commercially supplied by manufacturers.

Metal Chimney Flue

The innovation consists of interlocking metal tubes that exhaust the waste air from furnaces and fireplaces. Its advantages over masonry chimneys are that it has lower operating costs because the heating of the flue eliminates the need for force-drafting devices, its hotter inner walls prevent tarry condensation, and it has less joint erosion which causes drafts and high maintenance costs (Ventre, 1973). It is commercially supplied by manufacturers.

Pre-Insulated Ductwork

The innovation consists of ventilation ductwork covered with an insulating layer. Its advantages are that it can distribute hot or cold air with very low leakage and at a high velocity that then mixes well with the room air (Energy Design Update, 1988). It is commercially supplied by manufacturers.

Floor or Ceiling Plenum

The innovation consists of using the under-floor crawl space or a hall ceiling area as a heat distribution system. The plenum can be constructed from gypsum board. Its advantage is that it eliminates significant amounts of heating ductwork (U.S. Department of Housing and Urban Development, 1988b). It is not commercially supplied by manufacturers.

Flexible Gas Tubing

The innovation consists of corrugated stainless steel tubing which is used to pipe natural gas to appliances. Its advantages are that it eliminates elbows and threading machines needed for rigid piping, and it can be threaded through walls and under other surfaces with much less labor (Journal of Light Construction, May 1990, p. 67). It is commercially supplied by manufacturers.

Functional Area: Interior Finish

Gypsum Board

The innovation consists of hydrous calcium sulfate fabricated as slabs and covered with a paper sheet or other materials (including metal sheet, wire mesh, and reflective foils). It is also called "sheetrock" and "drywall." Its advantage is that it significantly reduces the time and labor required compared to plastering. It is commercially supplied by manufacturers.

Sheetrock Edge-bead

The innovation consists of a molded metal or plastic strip which is placed over the corner connections between sheets of gypsumboard. Its advantages are that it provides a cleaner line and more durable surface that other methods. It is commercially supplied by manufacturers.

Drywall Corner at Truss

The innovation consists of a clip on the top plate of the wall which backs the ceiling drywall at the corner for taping. Its advantages is that it compensates for any truss movement which could crack the drywall joint (Journal of Light Construction, May 1990, p. 65). It is commercially supplied by manufacturers.

Veneer Plaster

The innovation consists of a light layer of plaster over a base material, usually gypsum-board. Its advantage is that the resulting surface gives the feel of plaster without the high labor costs (Allen, 1985). It is commercially supplied by manufacturers.

Fiberglass Re-inforced Plaster

The innovation consists of sheets of fiberglass mesh covered with a plaster compound. Its advantages are that it is more resistant to surface damage, particularly in high use areas, and lasts longer than standard plaster (Allen, 1985). It is commercially supplied by manufacturers.

Expanded Metal Plaster Lath

The innovation consists of thin sheets of metal alloy slit and stretched to produce a mesh of diamond shaped openings, used as a base for plaster. Its advantages are that it requires less labor and material than wooden laths (Allen, 1985). It is commercially supplied by manufacturers.

Gypsum Plaster Lath

The innovation consists of a gypsum core with absorbent paper facing.

Its advantages are that it not only uses less material and labor than wood lath, but it also eliminates one coat of plaster (Allen, 1985). It is commercially supplied by manufacturers.

Plastic Trim/Molding

The innovation consists of molding plastic to resemble plaster or wood trim. Its advantages are that it may be less expensive than wood or plaster trim, and it may not require painting. It is commercially available from manufacturers.

Urethane Plaster Mold

The innovation consists of polyurethane plastic molds to cast plaster ornamentation. Its advantages are that it can provide duplicates more exactly and less expensively than those created by hand (Fine HomeBuilding, Number 50, p. 68; Fine HomeBuilding, Number 43, pp. 40-43). It is commercially supplied by manufacturers.

Solid Core Laminate

The innovation consists of a solid plastic laminate material. Its advantages are that it has an even color distributed throughout its depth, and it lasts longer than standard counter materials, but it cannot itself be used as a cutting surface because it scratches easily. It is commercially supplied by manufacturers.

Movable Height Counter/Cabinet

The innovation consists of a 110 volt electric motor with a worm-gear lift to change the height of counters or cabinets. Its advantage is its accessibility to wheel-chair bound or otherwise handicapped inhabitants (Journal of Light Construction, May 1990, p. 64). It is commercially supplied by manufacturers.

Plastic Sinks

The innovation consists of plastic molded into a sink shape. Its advantages are that it is lighter than porcelain or enamelized sinks, it can be molded in a variety of shapes and colors, and it can include backsplashes and counters in one unit. It is commercially supplied by manufacturers.

Vinyl Flooring

The innovation consists of plastic vinyl imbedded in large pre-formed sheets. Its advantages are decreased flooring costs and increased longevity. It is commercially supplied by manufacturers.

Masonite

The innovation consists of highly compressed wood pulp and fiber, generally used as an underlayer for carpeting and other flooring. Its advantage is that it is an inexpensive subfloor. It is commercially supplied by manufacturers.

Homosote

The innovation is composed of recyled wood fibers (e.g. newspapers) loosely compressed into sheets. Its advantage is that it provides sound deadening for flooring underlayment or inside wall and ceiling cavities. It is commercially supplied by manufacturers.

Suspended Acoustical Ceiling

The innovation consists of metal frames that hold acoustical panels made of fibrous materials. Its advantages are that it is less expensive than other ceiling systems, and can provide sound deadening (Allen, 1985). It is commercially supplied by manufacturers.

Latex Paint

The innovation consists of a water-soluble paint solution. Its advantages are that it is easier to clean the painting tools, and it avoids the toxic by-products and the cleaning solvents used for oil-based paints. It is commercially supplied by manufacturers.

Epoxy Grout

The innovation consists of epoxy resins, and contains no cement at all. Its advantages are that it resists crumbling, color spotting, and staining (Journal of Light Construction, November 1988, p.44). It is commercially supplied by manufacturers.

Appendix C: Manufacturers of Stressed-Skin Panels

C.0 Introduction

The purpose of this appendix is to provide a list of existing manufacturers of stressed-skin panels. I compiled this list through a review of the literature (notably Andrews, 1988; Carlson, 1988; and Arvin, 1985), complemented by industry sources. The products and packages available from these manufacturers may differ significantly. This list is for general information and research purposes rather than as a complete survey of manufacturers in this industry. Chapter 4 describes the market of stressed-skin panels.

While the research in this paper focused exclusively on solid foam-core panels manufacturered in the United States, some of the manufacturers in this list produce panels with wood framing members imbedded in the foam; other manufacturers in the list produce panels in Canada. For the purpose of comprehensiveness, these manufacturers were not excluded from this list.

Because the market is still volatile, some of these companies may no longer be producing stressed-skin panels for general sale. This list does not claim to include <u>all</u> companies which produce the panels; many construction companies which produce panels for their own use are not included.

List of Manufacturers of Stressed-Skin Panels

Advance Energy Technologies
P.O. Box 387
Clifton Park, NY 12065
518/371-2140

Advance Foam Plastics (see Associated Foam Manufacturers)
5250 North Sherman St.
Denver, CO 80216
303/297-3844

Affordable Luxury Homes
P.O. Box 288
Markle, IN 46770
219/758-2141

Alchem
3617 Strawberry Road
Anchorage, AK 99502
907/243-2177

Allied Foam Products (see Associated Foam Manufacturers)
1604 Athens Highway
Gainesville, GA 30501
404/536-7900

Andrews Building Systems
225 South Price Road
Longmont, CO 80501
303/759-1998

Associated Foam Manufacturers
P.O. Box 246
Excelsior, MN 55331
800/255-0176 or 612/474-0809

AFM is a group of independent foam manufacturers around the country who are licensed to manufacture R-Control panels. Established 1979, now has 35 member companies, including: (** five largest)

Selected Associated Foam Manufacturers:

1) Advance Foam Plastics **
5250 North Sherman St.
Denver, CO 80216
303/297-3844

2) Allied Foam Products
1604 Athens Highway
Gainesville, GA 30501
404/536-7900

3) Big Sky Insulations **
15 Arden Drive
Belgrave, MT 59714
406/388-4146

4) Branch River Foam Plastics **
15 Thurbers Blvd.
Smithfield, RI 02917
401-232-0270

5) Century Insulation Mfg. **
Industrial Park
Union, MS 39365
601/774-8285

6) EPS Molding **
2019 Brooks
Houston, TX 77026
713/237-9115

7) Insulated Building Systems
100 Powers Court
Sterling, VA 22170
703/450/4886

8) Pacemaker Plastics
126 New Pace Rd.
Newcomerstown, OH 43832
614/498-4181

9) Poly-Foam
116 Pine Street South
Lester Prairie, MN 55354
612/395-2551

10) Thermal Foams
2101 Kenmore Ave.
Buffalo, NY 14207
716/874-6474

11) Western Insulfoam
19041 80th Avenue South
Kent, WA 98032
206/242-9424
and: 1155 Industrial Drive
Dixon, CA 95620

12) Wisconsin EPS
90 Trowbridge Drive
Fond du Lac, WI 54935
414/923-4146

Atlas Industries
6 Willows Rd.
Ayer, MA 01432
508/772-0000 or 800/343-1437

Big Sky Insulations(see Associated Foam Manufacturers)
15 Arden Drive
Belgrave, MT 59714
406/388-4146

Branch River Foam Plastics (see Associated Foam Manufacturers)
15 Thurbers Blvd.
Smithfield, RI 02917
401-232-0270

Cano Structures/NASCOR System
MAIN OFFICE (also offices in Vancouver, Toronto, Arizona)
7803P 35th Street S.E.
Calgary, Alberta T2C 1V3
Canada
403/279-1966

Century Insulation Mfg. (see Associated Foam Manufacturers)
Industrial Park
Union, MS 39365
601/774-8285

Cheney Building Systems
2755 South 160th St.
New Berlin, WI 53151
414/784-9634 or 800/527-3895

Clark Industries
375 East Fifth Ave.
Columbus, OH 43201
614/294-3761

Concept 2000 Homes
3003 N. Highway 94
St. Charles, MO 63301
314/947-7414

Delta Industries
1951 Galaxie St.
Columbus, OH 43207
614/445-9634

Drew Foam of Colorado
1450 West Colfax Ave.
Denver, CO 80204

Elite Systems
444 Charmony, Frontage Road
Sterling, CO 80751
303/522-4010

Energy Saving Productions
40 Inverness Drive East #100A
Englewood, CO 80112
303/792-5656

Enercept
3100 9th Ave. S.E.
Watertown, SD 57201
605/882-2222

EPS Molding (see Associated Foam Manufacturers)
2019 Brooks
Houston, TX 77026
713/237-9115

Fischer Corp.
1843 Northwestern Parkway
Louisville, KY 40203
502/778-5577

Foam Laminates of Vermont
P.O. Box 102B
Hinesburg, VT 05461
802/453-4438

Foam Products
P.O. Box 2217
Maryland Heights, MO 63043
314/739-8100 or 800-824-2211

Foam Plastics of New England
P.O. Box 7075
Prospect, CT 06712
203/758-6411

Futurebilt
A-104 Plaza Del Sol
Wimberley, TX 78676
512/847-5721

Harmony Exchange
Rt. 2 Box 843-F
Boone, NC 28607
704/264-2314

Homasote Company
P.O. Box 7240
West Trenton, NJ 08628
609/883-3300

Insulated Building Systems (see Associated Foam Manufacturers)
100 Powers Court
Sterling, VA 22170
703/450/4886

Insul-Kor
201 E. Simonton
Elkhart, IN 46514
800/521-1402 or 219/262-3472

Insul-Wall
11 Mosher Drive
Dartmouth, N.S.
Canada B3B 1L8
902/465-7470

J-Deck Building Systems
2587 Harrison Rd.
Columbus, OH 43204
614/274-7755

Kondor Post and Beam Homes
The Business Park at Cambridge
RR1 Box 2794
Underhill, VT 05489
802/644-5598

Korwall Industries
326 N. Bowen Rd.
Arlington, Tx 76012
817/277-6741

Low-Temp Engineering Inc.
308 East Main Street
Route 123
Norton, MA 02766
617/285-9788

Murus Company
P.O. Box 220, Dept. MF
Mansfield, PA 16933
800/626-8787

Northern Energy Homes
P.O. Box 463
Norwich, VT 05055
800/223-6092 or 802/649-1348

NRG Barriers
15 Lund Rd.
Saco, ME 04072
207/283-8000

Pacemaker Plastics (see Associated Foam Manufacturers)
126 New Pace Rd.
Newcomerstown, OH 43832
614/498-4181

Panel Building Systems
431 Second St.
Reynolds Industrial Park
Greenville, PA 16125
412/646-2400

Poly-Foam (see Associated Foam Manufacturers)
116 Pine Street South
Lester Prairie, MN 55354
612/395-2551

Pond Hill Homes
Westinghouse Rd.
RD4 Box 330-1
Blairsville, PA 15717
412/459-5404

RADVA
P.O. Box 2900, FSS
Radford, VA 24143
703/639-2458

Red Suspenders Timber Frames
Route 7, Box 8383
Nacogdoches, TX 75961
409/564-9465

Riverbend Timber Framing
P.O. Box 26
Blissfield, MI 49228

Sunlight Homes/Polytherm Corp.
Box 4366
Albuquerque, NM 87196
800/327-5835 or 505/867-2366

Thermal Foams (see Associated Foam Manufacturers)
2101 Kenmore Ave.
Buffalo, NY 14207
716/874-6474

Therm-L-Tec Systems
119-A Osage
Kansas City, KS 66105
913/621-1916

Thermapan Industries
2514 Highway 20, Box 479
Fonthill, ON
Canada L0S 1E0
416/892-2675

TimberFrame Systems
Main Street
P.O. Box 458
Frankford, DE 19945
302/732-9428

Unijoint International
Division of R.J. Rydeen & associates
107 Main St.
P.O. Box 107
Fremont, NH 03044

United Industries
P.O. Box 715
Bentonville, AR 72712
501/273-2924

Vermont Stresskin Panels
The Business Park at Cambridge
RR#1, Box 2794
Cambridge, VT 05444
802/644-8885

W.H. Porter
P.O. Box 1138
Holland, MI 49422
616/399-1963

Western Insulfoam (see Associated Foam Manufacturers)
19041 80th Avenue South
Kent, WA 98032
206/242-9424

Winter Panel
RR5 Box 168 B
Glen Orne Drive
Brattleboro, VT 05301
802/254-3435

Winter, Inc.
Main St.
West Groton, MA 01472
617/448-3077

Wisconsin EPS (see Associated Foam Manufacturers)
90 Trowbridge Drive
Fond du Lac, WI 54935
414/923-4146

Appendix D: Bibliography of Literature Relating to Innovation in Residential Construction

D.0 Introduction

During the course of this research, I identified many studies of innovation in the residential construction industry. While space does not permit me to discuss each and every one of these studies, this selected bibliography can aid further research on innovation in this industry through reference to existing work.

The references included in this bibliography concern either the generation of innovations or their application and acceptance in the industry. A few of the studies analyze specific innovations, but the majority consider the context of the industry overall for the development and adoption of innovations.

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