U.S. Department of Housing and Urban Development
Office of Policy Development and Research

Design for a Cold-Formed Steel Framed Manufactured Home:

Technical Support Document

Final Report

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About the Manufactured Housing Research Alliance

The Manufactured Housing Research Alliance (MHRA) is a non-profit organization with the mission of developing new technologies to enhance the value, quality, and performance of the nation's manufactured homes. The MHRA's research supports the industry by developing new methods for using manufactured homes in a wide array of housing applications, by solving technical challenges, and by paving the way for innovations in home design, construction, and installation.

To carry out its mission, the MHRA develops, tests, and promotes better methods and materials for designing, manufacturing, and marketing HUD-code homes. These activities include research, new product development, training and educational programs, testing programs and demonstrations, commercialization efforts, workshops, conferences and other events.

MHRA has over 400 members who build more than 80 percent of new manufactured homes.

PREFACE

HUD in the past several years has focused on a variety of innovative building materials and systems for use in residential construction that promote healthy competition and help define optimal use of all our natural resources while enhancing affordability.

Home manufacturing is a wood framed based industry. The HUD-code industry has grown up around wood framing technology and significant time and expense have been invested in value engineering wood as the structural material of choice. The manufacturing process is based on lumber dimensions, material assembly methods and other building materials traditionally used in conjunction with wood framing. However, relative to wood, cold-formed steel possesses a compelling set of material properties. Steel is lightweight, fireproof, vermin resistant, dimensionally stable (not subject to material decay, warping and twisting and shrinkage) and can be fabricated to a wide range of shapes and sizes with virtually no material wastage.

There are additional factors that suggest the industry would be well advised to consider options to wood as the basic structural building block. Foremost among these are the uncertainties associated with future wood resources and the historic price fluctuations that at times have made wood more expensive than steel. Even if steel proved to be less attractive than wood in the short term, as a future alternative material, steel shows considerable promise.

The Design for ***Cold-formed Steel Framed Manufactured Home: Technical Support Document*** summarizes the results of the first phase of a multiphase effort to assess viability of substituting steel for wood as the structural skeleton of homes built under the HUD manufactured home standards.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

Project Overview

The use of cold-formed steel in the structural system of residential construction has taken hold in some site building markets but potentially offers far more value to the manufactured home industry. The Manufactured Housing Research Alliance (MHRA) is coordinating an effort to develop a market competitive structural design, based on cold-formed structural steel technology and suitable for the home manufacturing environment. This report summarizes findings of the first phases of the research. The effort is a cooperative undertaking of MHRA, the Manufactured Housing Institute (MHI), several home manufacturers, the North American Steel Framing Alliance (NASFA) and the US Department of Housing and Urban Development (HUD).

Home manufacturing has historically been a wood framed based industry. The HUD-code industry has grown up around wood framing technology and significant time and expense have been invested in value engineering wood as the structural material of choice. The manufacturing process is based on lumber dimensions, material assembly methods and other building materials traditionally used in conjunction with wood framing. However, relative to wood, cold-formed steel possesses a compelling set of material properties. Steel is lightweight, fireproof, vermin resistant, dimensionally stable (not subject to material decay, warping and twisting and shrinkage) and can be fabricated to a wide range of shapes and sizes with virtually no material wastage.

There are additional factors that suggest the industry would be well advised to consider options to wood as the basic structural building block. Foremost among these are the uncertainties associated with future wood resources and the historic price fluctuations that at times have made wood more expensive than steel. Even if steel proved to be less attractive than wood in the short term, as a future alternative material, steel shows considerable promise.

This phase of the research was shaped by the following two overriding objectives:

- Demonstrate that it is possible to produce a cold-formed steel framed home at about the same or at a lower first cost than a comparable wood framed system;
- Demonstrate that such a design can comply with the Federal Manufactured Home Construction and Safety Standards.

In a process that started in 1998, the project team evolved a steel frame design that satisfied both objectives. The major product of this study is a design for a prototype home, documented in this report, consisting of a structural frame made entirely of cold-formed steel components that is cost competitive with a comparable wood frame design. The design has been reviewed by a Design

Inspection Primary Inspection Agency (DAPIA)[1] and deemed to be in compliance with the Federal Manufactured Home Construction and Safety Standards (FMHCSS).

This research covers important ground and better defines those issues whose resolution is expected to result in the economic and technical viability of steel frame for HUD-code applications. Additional study is needed to more completely demonstrate that cold formed steel framing is competitive with wood framing, and this work takes the necessary first steps in moving the technology forward.

The discussions that follow provide a history of the effort and a summary of the resources and expertise invested in the study. Subsequent sections describe the prototype design together with engineering documentation and recommendations for the subsequent steps required to demonstrate the viability of steel for manufactured housing construction.

The Design Development Process

The following is a summary of the project history and major milestones:

Work on the cold-formed steel framing project was started in April 1998. In the initial months, several meetings were convened with industry organizations interested in the technology. Several manufacturers interested in cold-formed steel framing were polled to establish impediments to the technology. Representatives of about 35 companies with a potential stake in steel technology attended an exploratory meeting in Nashville, TN on October 28, 1998.

A Steering Committee guiding this work established research priorities including demonstrating that steel framed homes, on a material basis alone, were potentially cost competitive with wood framed homes. Foremost among the conditions placed on the development process by the Steering Committee was that the cold-formed steel design not stray far from current wood framing construction practices (for example, apply a stud-to-stud replacement approach) and manufacturing methods.

The design process had several integrated goals. First and foremost the Committee and sponsors suggested developing a design that any manufacturer could readily modify to fit a house style and present for DAPIA approval. The approach, therefore, was to develop from a typical industry home configuration, a structural package that was approvable by a DAPIA. (The basic features of this typical configuration are described in Appendix B.) The material cost of this design was compared against the same home configuration but using wood framing. The Committee also directed that design strategies be developed that in a cost-effective manner comply with the HUD thermal requirements. Emphasis was placed on Thermal Zones I and II with future consideration to solutions that would work in the colder Zone III states. The effort included demonstrating compliance with the thermal standards for these regions.

The preliminary structural design was more expensive than wood framing on a material cost basis. However, the Committee recognized that this first cut could be improved upon and a design subgroup was appointed to value engineer the design, update the DAPIA review and revise the cost analysis. The improved and updated designs that resulted from the work of the subgroup, and the associated cost analysis are reported in this document and include the following information:

- Prototype cold-formed steel design with value engineering improvements – Section 2
- Structural engineering analysis– Section 3 and Appendices

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[1] The DAPIA plays a key role in the acceptance and adoption of new technology by the manufactured housing industry. It is the DAPIA that must review and approve the manufacturers design plans and certify that they are in accordance with the nationally preemptive Manufactured Home Construction and Safety Standards.

- Cost analysis– Section 4
- Thermal analysis – Section 5

This report represents a midpoint in a process that is evolving a complete scenario for a cold-formed steel home manufacturing system of which the design is one crucial part. Other pieces need to be developed before the technology is of proven value in the home manufacturing environment. To that end, Appendix C presents recommendations for follow on work intended to pick up where this effort leaves off.

Inventory of Steel Framing Technology

The project investigations capitalized on the many resources available in the public domain, the topical literature and private efforts to discover and bring to market cost competitive steel framing technologies. The steel industry, notably through NASFA and the American Iron and Steel Institute (AISI), is the repository of much of this information and was an invaluable resource for this project. In addition, through the course of this work, the products and services of several companies emerged as being particularly valuable to any home manufacturer interested in embracing cold-formed steel framing. A list of these companies is provided in Appendix D.

Milestones in the Adoption of Cold-formed Steel Framing

Changing traditional practice, regardless of the advantages and long-term benefits, is almost always a challenge. When it comes to new methods of building, particularly those like cold-formed steel framing that are not visible in the finished home and therefore may be difficult to market, the manufactured home building industry is necessarily conservative. The financial and/or marketing advantages must be compelling. Even then, building sufficient market share requires a strong belief in the change and a commitment on the part of the manufacturer and the sales force to integrate the technology into current practices and to build and sustain market share.

This effort marked the beginning of a public-private cooperative undertaking for the purpose of resolving many of the technical hurdles that have slowed the residential use of steel framing. In a systematic way, the work is intended to remove or address the barriers that manufacturers see or perceive as impediments to using steel for home fabrication. As the barriers fall, and ways to cost-effectively use steel for manufactured home construction emerge, the technology will gain an industry foothold. This requires a continual process of articulating and finding ways to surmount the barriers to the technology.

The argument for steel framing hinges on cost: if building homes with cold-formed steel in place of wood reduces the overall cost of home production, the technology will have a receptive audience. This study suggests that measured by material cost alone, steel looks promising. The current work also established that steel could be used in conformance with the HUD standards. These findings achieve the goals established by project sponsors and participating home manufacturers.

In the course of this project, two first tier issues emerged as central to industry's serious consideration of steel as a viable alternative to wood: first cost and acceptance under the HUD code. Cost, particularly first cost drives decisions in the manufactured housing industry to a far greater degree than other housing sectors. The primacy of cost stems from the fact that industry's core product is affordable housing and even small increases in price can adversely impact competitiveness and the homebuyer's to qualify for the home.

Further, the steel solution was restrained by the condition that it not displace any of the other materials or production practices common in manufactured housing production. This translates into a fairly rigid steel stud for wood stud replacement approach. This strategy may not play into the strengths of steel but the resulting design has the least possible impact on current practices. (This condition was later revised to allow different stud spacings for steel versus traditional wood practices.)

The other main goal of the current phase of the research, demonstrate acceptance of steel framing under the HUD-code, placed the emphasis on developing a prototype design and providing the kind of supporting analysis typically required to obtain DAPIA approval. These efforts established that the HUD-code does not intrinsically prohibit the use of steel as a structural substitute for wood and work described herein offers a template and engineering basis for manufacturers to obtain such approvals in the future.

In approving the design of cold-formed steel framed home, the DAPIA is mainly concerned with the home's structural subsystem and thermal subsystems, the major areas of emphasis for this work. Evolving a viable structural design using steel framing resulted from a three-way dialogue between MHRA project coordination staff, the structural engineering firm of Anderson-Peyton and DAPIA RADCO. The results of this part of the design process are described in **Section 2: Structural Design and DAPIA Review.**

Although not part of the DAPIA review, the research investigated thermal performance as a potential barrier to the use of steel framing. Steel is a better conductor of heat than wood an achieving equivalent thermal performance is generally more expensive with steel. The thermal consequences of using steel were investigated with HUD Thermal Zone 1, an area in the southern part of the nation that contains the majority of new manufactured home shipments. As discussed in **Section 3: Thermal Envelope Design**, the steel design can meet the HUD requirements for Zone 1. This analysis will form the basis for developing the more thermally efficient designs that will be needed in the colder, northern climate zones.

The Committee overseeing the project recognized the fact that the real financial consequences of switching from wood to steel involves quantifying not only material cost differences but also impact on such factors as speed of production, inventory costs, labor training and many other hard and soft costs. However, reflecting the realities of how industry approaches the adoption of new construction methods—that it not increase and preferably reduce material cost—comparing wood and steel on this basis was made a cornerstone of this initial phase of the research.

The first cost comparison described in **Section 4: Cost Analysis**, must be understood in this context and given significant weight when considering the economic consequences of switching from wood to steel framing. The results of this comparison are compelling—the steel framed home is less expensive than its wood framed counterpart. The relative costs of the two materials will change and there are reasons to believe that steel might, indeed, be more cost competitive in the near future as technical hurdles are overcome, the material is used in a more creative fashion and the industry talent for value engineering, so effectively applied to wood systems over the last three decades, is focused on steel framing.

This effort was a valuable first step in helping cold frame steel framing establish a place as a viable alternate framing method for manufactured housing. Additional research and investigation, outlined in **Section 5: Next Steps** will help prove the technology and set the stage for its future commercialization.

2

STRUCTURAL DESIGN AND DAPIA REVIEW

Evolution of the Structural Design

In contrast to site building where cold-formed steel framing has made market inroads, manufactured housing relies entirely on wood for the home's structural skeleton. Steel is used routinely for the home's supporting chassis and to support the floor joists, and in a few instances for perimeter floor framing in what is referred to a unified floor construction. A few manufacturers are investigating or using specialty floor systems that consist of steel floor joists often placed at non-standard spacing (i.e. 32 in. on center). Otherwise, and until this study, the industry has not considered steel as a viable alternative to wood.

Despite the fact that many of the technical issues associated with using cold formed steel have been the subject of R&D and ongoing work—notably conducted by the National Association of Home Builders in collaboration with the North American Steel Framing Alliance and the US Department of Housing and Urban Development—HUD-code homes pose an essentially new set of technical hurdles and a clean slate for manufactured housing. Practical and basic questions, such as, can cold-formed steel framing satisfy the requirements of the HUD code and economically compete with wood were by no means settled when this effort started and answering these important questions evolved into the major focus of this study.

The research strategy relied on demonstrating that cold-formed steel could be used under the HUD standards by adapting the frame from a common double wide design contributed by one manufacturer but similar to designs used by many companies. Participating manufacturers agreed that this approach would yield a design that any company could adapt to their proprietary product line. The critical challenge was demonstrating that the Design Approval Plan Inspection Agencies (DAPIAs), companies certified by HUD to check compliance with the federal standards, would approve a home framed in cold-formed steel. An approval of a representative design by one DAPIA would provide the model for a raft of derivative designs to be developed by any manufacturer and approved by other DAPIAs.

To simplify the design and approval process the design conditions were limited to HUD Thermal Zone 1 and Wind Zone 1, the least stringent areas for both design factors. Also, the geographical area that is the confluence of these two criteria contains the majority of new home sales and most likely to be the site for pilot steel framed home manufacturing demonstrations. Other design parameters included the following:

General Design Criteria

Design Code/Standard

- Manufactured Home Construction and Safety Standards (MHCSS)

Design Loads

- Wind Zone I, 15 psf horizontal, 9 psf uplift, 22.5 psf for overhangs
- Roof Live Load, South Zone, 20 psf

- Thermal Zone 2, overall U_o-value = 0.096

Model criteria

Floor Plan

- Box dimensions – 28 x 56 ft., two section with cathedral ceiling
- Chassis – 99 in. on center twin rail frame with outriggers
- Floor width – 162 inches each section
- Floor joints – 16 in. on center
- Sidewall height – 90 in.
- Roof Pitch – nom. 3/12
- Roof trusses – 24 in. on center
- Eaves – 6 in. sidewall overhang
- Cathedral ceiling – ceiling height at mating line approx. 107 in.
- Attic insulation – blown cellulose
- Ridge beam – not to be exposed by extending below ceiling at mating line (23 in. maximum depth)
- Mating line walls to be load bearing in each half wit h 2' x 4 in. studs at 16 in. on center
- Interior wall framing to be 2' x 3 in. 24 in. on center except for shearwalls

Exterior Coverings

- Roof – 205 lb. composition shingles over 7/16 in. oriented strand board
- Walls – 7/16 in. hardboard

Interior Wall Coverings

- Gypsum wall board, pre-finished and/or tape and textured
- Ceiling Board – ½ in. gypsum board

Floor Covering

- 40 percent roll goods, 60 percent carpet
- 19/32 in. D-3 particleboard, 4 x 8 ft. sheets perpendicular to joists

Utilities

- Water system – PEX, flexible pipe support details
- DWV system – ABS in floor to extent possible, support details
- Electrical system – NMC cable, protection and support details, j-box connection and support methods
- HVAC duct system – 5 x 12 in. metal duct in floor, center run
- Air infiltration envelope shall be considered to be the interior wall paneling of the exterior walls when developing structural connection details.
- To be compatible with the typical manufacturing facility and process in use at this time.

Major findings

In the process of developing the structural solution for using cold formed steel framing in the fabrication of manufactured homes, the Committee cited the following as opportunities for advancing the work:

- Cold formed steel is a viable structural alternative to wood that can be shown to meet the requirements of the HUD standards. The design documented in this report was reviewed by RADCO, one of the nation's leading DAPIAs, and found to be in conformance with the standards.
- The pursuit of design alternatives was confined to the current structural design methodologies. Steel studs were used on virtually a one-to-one replacement basis of wood. The opportunity exists to develop more imaginative and potentially more cost effective solutions using cold formed steel in the future.
- Hybrid designs also deserve consideration. For example, it may be more cost effective to use cold formed steel in conjunction with wood in some instances (such as steel floors and walls with wood trusses).
- Future development of steel designs should include suppliers that might contribute proprietary solutions that are more cost effective and flexible than those documented in this report. For example, companies like Alpine, Studco, or Mitek have proprietary truss shapes that could prove to be economical alternatives to the prototype.
- The area of fasteners is rapidly evolving and will be one of the major factors that determine the future viability of steel framing in manufactured housing. These developments should be closely monitored.
- More testing is needed to demonstrate the soundness of using cold formed steel framing in more economical and structurally efficient ways. A discussion of testing is provided in Appendix C.

A more detailed discussion of the decisions leading to the development of the prototype and the design details and specifications is provided in Appendix B. This information constitutes the complete documentation of the structural design package that was reviewed by the project DAPIA and found to be in compliance with the HUD code (see Appendix A for DAPIA letter). The appendix also provides some suggestions for changes that could lead to cost reduction and/or value engineering of the prototype.

3

THERMAL ANALYSIS

Thermal Conductance Calculation Methods for Manufactured Housing with Steel Framing

As an alternative to traditional wood framing, steel framing has many advantages. However, thermal performance is an area of potential weakness requiring design approaches that minimize the inherent properties of steel.

Steel is characterized by high thermal conductivity providing a ready path for heat flow. Indeed, steel is so effective at heat transference that a steel structural component creates what is referred to as a "thermal bridge." Successful strategies for reducing heat flow with steel framing often depend on minimizing the steel cross sectional area, and therefore the available path area for heat flow, and/or placing a continuous layer of insulation on the exterior side of the steel effectively short-circuiting the heat flow path.

The relative importance of thermal strategies increases mainly with the size of the heating load. As will be evident by the discussions that follow, identifying strategies for insulating cold-formed steel that meet the thermal requirements for HUD Thermal Zone I is not a difficult task. Complying steel framed homes in HUD Thermal Zone III, without incurring a significant increase in cost, is a challenge.

Adding to the difficulty of the task of finding thermal solutions for steel framed homes is the lack of consensus regarding the procedures for modeling heat flow through building components. The simplified parallel heat path heat transmission procedure used for wood frame construction is not a reliable predictor of heat flow through steel framed constructions.

There is general agreement within the engineering community on a method for modeling heat flux through walls and the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) publishes a "modified zone method" for this purpose. While, information for estimating heat transmission though steel floors and ceilings are available, the accuracy of these procedures generally, and their applicability to manufactured home construction methods specifically, is in question.

For the most part, the values embedded in these procedures were derived experimentally using ASTM test procedures and based on a limited sample of building sections that did not include manufactured home designs (such as the design described in this document). As this document goes to press, the North American Steel Framing Alliance in coordination with Oak Ridge National Laboratory is planning to conduct testing that will provide data to improve the modeling of steel frame buildings. MHRA will work with NASFA and ORNL to include manufactured housing prototypes in the testing process.

As an approximation, MHRA used the existing analytical methods for designing the thermal envelope for the cold-formed steel design. The approach taken in analyzing each building component is described in the discussions below.

Estimating Heat Flow through Steel Truss Ceiling Assemblies

For ceiling assembly sections with steel frame truss construction, U-values have been obtained experimentally to correct for the effects of thermal bridging as shown on Table 3-1. This table lists U-values for clear ceiling sections with cavity insulation from R-19 to R-49 and for spans from 8 feet to 50 feet in length.

The data were obtained using 2 x 4 in. steel constructions, thus the U-values reported here will be conservatively high. Actual truss dimensions are 1⅝ x 1¼ in. for the MHRA steel home design. Since this is experimental data was originally intended to apply to typical dimensional lumber, 2 x 4 in. was the smallest component considered. Since 1⅝ and 1¼ in. steel members will have more insulation coverage (i.e., less thermal bridging), using the factors derived from 2 x 4 in. material is conservative.

Table 3-1 Steel Truss Framed Ceiling U-values

Cavity Insulation R-Value	**Truss Span (feet)**												
	One King Post					**Two Bays**			**Three Bays**				
	8	10	12	14	16	16	18	20	22	24	26	28	30
19	0.0775	0.0717	0.0678	0.0650	0.0630	0.0695	0.0671	0.0653	0.0661	0.0646	0.0634	0.0623	0.0614
30	0.0607	0.0549	0.0510	0.0482	0.0462	0.0527	0.0503	0.0485	0.0493	0.0478	0.0466	0.0455	0.0446
38	0.0544	0.0485	0.0446	0.0419	0.0398	0.0463	0.0440	0.0421	0.0429	0.0415	0.0402	0.0391	0.0382
49	0.0489	0.0431	0.00392	0.0364	0.0343	0.0408	0.0385	0.0366	0.0375	0.0360	0.0347	0.0337	0.0327

Cavity Insulation R-Value	**Truss Span (feet)**										
	Four Bays					**Six Bays**					
	30	32	34	36	38	40	42	44	46	48	50
19	0.0666	0.0655	0.0645	0.0636	0.0628	0.0620	0.0614	0.0632	0.0625	0.0619	0.0614
30	0.0498	0.0487	0.0477	0.0468	0.0460	0.0452	0.0446	0.0464	0.0457	0.0451	0.0446
38	0.0434	0.0434	0.0434	0.0434	0.0434	0.0434	0.0434	0.0400	0.0394	0.0388	0.0382
49	0.0380	0.0368	0.0358	0.0349	0.0341	0.0334	0.0328	0.0345	0.0339	0.0333	0.0328

Notes:

1. Table excerpted from: McBride, Merle F., “International Code Committee Proposed Code Changes to the International Energy Conservation Code on Residential Steel Framed Ceilings and Floors, Report No. OC-CR-99-1, Owens Corning Science and Technology Center Granville, Ohio, 1999.
2. Assembly U-values in Table 1 are based on 24 in. center truss spacing and ½ in. in. drywall interior; all truss members are 2 x 4 in. “C” channels with a solid web.
3. The U-values on this Table are currently being recalculated through experimental analysis at the Oak Ridge National Laboratory Building Technology Center sponsored by the American Iron and Steel Institute. Values using typical manufactured housing truss framing dimensions (1⅝ x 1¼ in.) may be obtained as well.

Estimating Heat Flow through Steel Framed Walls

Unlike ceilings and floors, a procedure does exist for estimating heat flow through steel framed walls that is widely accepted and endorsed by ASHRAE. This procedure is referred to as the Modified Zone Method, and is described in the 1997 ASHRAE Handbook of Fundamentals. (A web-based calculator for using the method can be found at the following Oak Ridge National Laboratory (ORNL) web site address: http://www.ornl.gov/roofs+walls/mod_zone/modzone.html.)

The Modified Zone Method is similar to the Parallel Path Method typically used for calculating heat flow through constructions framed with wood. The main difference being the two methods is in how area zone of influence (*w* in the figure below) is estimated. In the Parallel Path Method, *w* is assumed to be equal to the length of the stud flange (L). In the Modified Zone Method, *w* is determined by the equation:

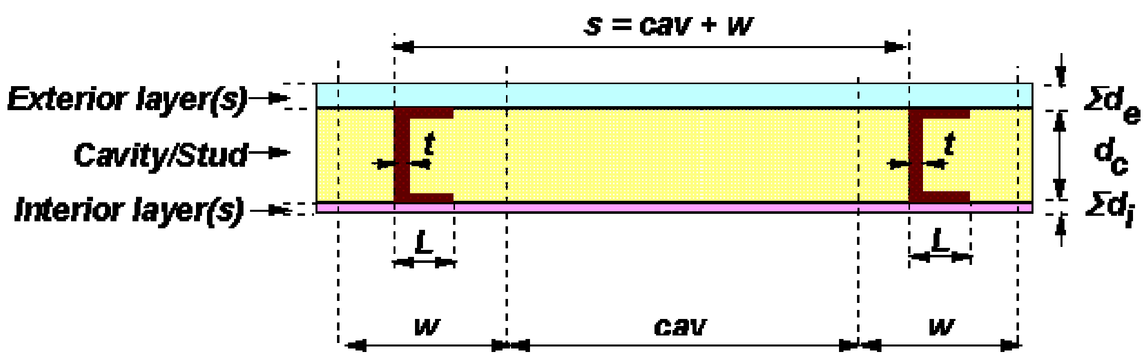
$$w = L + z_f * \text{(total thickness of all finish material layers on thicker side)}$$

Where:

z_f is an adjustment factor that depends on the ratio between thermal resistivity of finish material and cavity insulation, size (depth) of stud, and thickness of finish material layers. 1997 ASHRAE Fundamentals 24.14 describes how to arrive at an appropriate z_f. For the "zone method", $z_f = 2$; for the modified zone method the appropriate value for z_f depends on the ratio of the Average resistivity of sheathing and face materials/Resistivity of Cavity insulation, and the total thickness of the materials.

The accuracy of the Modified Zone Method was verified by detailed finite-difference computer modeling of over 200 metal frame walls with insulated cavities [Kosny 1995]. The Modified Zone Method results were within $^{+/-}$2 percent of the detailed computer modeling results.

Figure 3-1 Steel frame wall section showing the thermal bridge zone of influence *w*.



Estimating Heat Flow through Steel Framed Floor Assemblies

Steel framed floors in manufactured housing offer a unique modeling challenge since the steel framing spans the length of the floor assembly and the makeup depth of the assembly is not uniform. Lacking empirical data for this composite design condition, estimates for the heat transfer coefficient of the floor were made using the approach described below.

The midsection floor U-value is calculated as described in ASHRAE 1989 Fundamentals, except that the steel joists in the midsection area are assigned an R-value of 0. Sample calculations described in ***Overall U-Values and Heating/Cooling Loads – Manufactured Homes*** (3) describe the use of R-value for framing in the interior floor area. When insulation is abutting the floor joist, the R-value of the joist can be considered in calculating the total R-value of the floor. When the R-value in not abutting the floor joist, it is considered to be within the heated floor cavity space. Therefore, the effective R-value in such a cavity is considered to be zero. Steel joists will be at the temperature of the floor cavity regardless of contact with the insulation below and will have an R-value of zero.

The outrigger section U-values are calculated using the correction factors shown on in Table 3-2. The values embedded in this table were derived using an experimentally validated computer analysis of a horizontal steel frame building assembly (see Figure 3-2).

Although these values were originally developed for horizontal ceiling assemblies, they are generally regarded by the building science community as the best values currently available to approximate a horizontal floor.[2] The separate U-values for each section are then combined into a single weighted average value.

Table 3-2 Averaged Framing Factors For Floor Assemblies with Steel Framing (F_c)

Framing Size	Spacing	Nominal Cavity R-Value				
		R-11	R-19	R-30	R-38	R-49
2x4	16 in. on center	0.49	0.77	0.86	0.89	0.92
2x6		0.38	0.51	0.72	0.78	0.83
2x8		0.37	0.30	0.51	0.63	0.71
2x4	24 in. on center	0.60	0.84	0.90	0.92	0.94
2x6		0.50	0.61	0.80	0.84	0.88
2x8		0.49	0.41	0.62	0.71	0.78

Note: Table excerpted from 2000 ICC Code Change Proposal to the IECC Section 502.2.1.2 Roof Ceiling, 27 October, 1999 American Iron and Steel Institute (AISI)

The U-value of the steel frame assembly is given as:

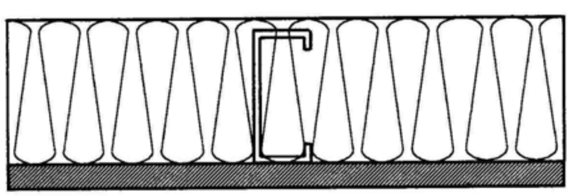
$$U_a = 1/(R_s + (R_{ins} * F_c))$$

Where:

U_a = the corrected U-value when using steel framing
R_s = total thermal resistance of all the other elements of the assembly excluding the cavity insulation and the steel stud
R_{ins} = the R-value of the cavity insulation
F_c = the correction factor listed in the accompanying table

The R-value for the steel stud is contained within the correction factor F_c. Because of the thermal bridging effect of steel it's resistance to heat transfer is only considered in the context of its assembly with surrounding materials.

Figure 3-2 The AISI horizontal steel frame assembly model.



Values for Table 3-2 were calculated assuming this configuration. Note that, when the insulation depth is deep enough, it is assumed to cover the top of the steel section.

[2] The values in Table 3.2 are used only for the outside section of the floor (outrigger sections). The floor construction in the outside sections closely resembles the ceiling construction for which the values in the Table were developed. It may not be valid to treat the midsection and outrigger floor sections as separate heat paths. In reality heat will migrate along the joists into the more conductive outrigger section.

Steel Versus Wood: Achieving Equivalent Thermal Performance

On Table 3-3 through Table 3-6, specific results are provided from an analysis that compares two homes, one framed in wood and the other in steel, but otherwise identical[3]. The methods used to calculate these values are described above.

The results, summarized in Table 3-6 illustrates how the framing alone has a significant impact on U_o-value with the wood frame home achieving a value of 0.074 compared with the steel home value of 0.086. The wood framed home design meets the HUD Thermal Zone III requirement while the steel frame home falls short of the required value of 0.079. Getting the steel framed home to pass in this climate is achievable but would require taking additional steps, such as applying an insulating board to the exterior walls.

Table 3-3 Overall U-value Calculation for Ceiling Assemblies: Wood versus Steel

	Wood Frame				**Steel Frame**
Component	Cavity (not restricted)	Cavity (restricted)	Frame (not restricted)	Frame (restricted)	
Inside Air Films	0.61	0.61	0.61	0.61	See Table 1 Use R-19, length 26 ft.
½ in. gypsum board	0.45	0.45	0.45	0.45	
Insulation	20.00	18.33	14.45	12.78	
Framing (1½ in.)	0.00	0.00	1.88	1.88	
Outside air film	0.61	0.61	0.61	0.61	
Total R-value	21.67	20.00	18.00	16.33	
U-value	0.046	0.050	0.056	0.061	0.063
Area	1303	67	98	5	1474
UA (U-value x area)	60.145	3.354	5.450	0.309	93.423
Total UA		**69.26**		**Total UA**	**93.42**
Total ceiling area		**1474**		**Total ceiling area**	**1474**
Wood ceiling U-Value		**0.047**		**Steel ceiling U-Value**	**0.063**

[3] Analysis is based on a three bedroom, two bath 1,493 sq. ft. double section 28 x 60 ft. home with nominal insulation values of R-30 ceiling, R-11 wall and R-22 floor and double, low-E windows.

Table 3-4 Overall U-value Calculation for Walls: Wood versus Steel

Component:	**Wood frame (16 in. on center)**			**Steel Frame (24 in. on center)**		
Layer descriptions	Cavity	Stud	Windows	Doors	Wall	
Inside air films	0.68	0.68	(Double/ low-E)		0.68	Value obtained through Modified Zone Method Analysis
½ in. gypsum board	0.45	0.45				
Insulation	11.00	0.00			8.43[4]	
Framing (2 x4 in.)	0.00	4.38				
7/16 in. hardboard	0.67	0.67				
Outside air film	0.17	0.17			0.17	
Total R-value	12.97	6.35			9.28	
U-value	0.077	0.157	0.39	0.22	0.108	0.390
Area	902	159	180	36	1062	180
UA (U-value x area)	70	25	70	8	114	70
Total UA			**173**	**Total UA**		**192**
Total wall area			**1278**	**Total wall area**		**1278**
Wood wall U-Value			**0.135**	**Steel wall U-Value**		**0.151**

Table 3-5 Overall U-value Calculation for Floor Assemblies: Wood versus Steel

Component	**Wood Frame** (16 in. on center)				**Steel Frame** (24 in. on center)	
Path names	Outside		Interior		Outside	Interior
Layer descriptions	Cavity	Framing	Cavity	Framing		
Inside air films	0.92	0.92	0.92	0.92	0.92	0.92
Carpeting	0.64	0.64	0.64	0.64	0.64	0.64
Floor decking	0.74	0.74	0.74	0.74	0.74	0.74
Insulation	18.92		22.00	22.00	11.54	22
Air space	0		1.22	1.14	0	1.22
Framing (2x6)	0	6.88	0	6.88	0	0
Insulation at framing	0	2.75	0	0	0	0
Outside air film	0.92	0.92	0.92	0.92	0.92	0/92
Total R-value	22.14	12.85	26.44	33.24	14.76	26.44
U-value	0.045	0.078	0.038	0.030	0.068	0.038
Area	446	50	865	96	495	962
UA (U-value x Area)	20	4	33	3	34	36
Total UA		**80.67**	(UA value includes ducts)	**Total UA**		**91**
Total floor area		**1607**		**Total floor area**		**1607**
Wood floor U-Value		**0.050**		**Steel floor U-Value**		**0.057**

[4] Value determined by using Modified Zone Method internet-based calculator provided by Oak Ridge National Laboratory (http://www.ornl.gov/roofs+walls/mod_zone/modzone.html).

Table 3-6 Comparison of Overall Thermal Coefficient of Heat Transmission (Uo-values) for Wood and Steel Framed Homes

Component	Component area (sq. ft.)	Wood framing component UA	Steel framing component UA
Ceiling	1474	69	93
Walls	1278	173	192
Floor	1607	81	91
Totals	**4358**	**323**	**377**
	Uo-value	**0.074**	**0.086**

Another way to illustrate the difference in thermal requirements as a function of framing material is to compare changes that would be required to bring a steel frame home into compliance with the HUD standards. Examples are provided on Table 3-7 and Table 3-8 for this purpose.

For example, a home in HUD Thermal Zone I might require insulation values of R-11 in the ceiling, R-11 in the walls and R-11 in the floor with a window area of 22 percent of the floor area and windows that are single glass with a storm. To bring the same home into compliance would require either increasing insulation in the ceiling to R-22, reducing the glass area to 10 percent and increasing the ceiling insulation value to R-14 or other options such as those shown on Table 3-7.

Table 3-7 Alternatives for achieving Equivalent Thermal Performance for Wood and Cold-formed Steel Framed Homes in HUD Thermal Zone I

Thermal Package Description[5]	Ceiling insulation	Wall insulation	Floor insulation	Window type	Glass area (percent)
WOOD FRAMED HOME					
Basic Wood Frame Design	11	11	11	Single w/storm	22
COLD-FORMED STEEL FRAMED HOME					
1. Increased insulation (1)	22	11	11	Single w/storm	22
2. Increased insulation (2)	16	11	19	Single w/storm	22
3. Reduce glass area	14	11	11	Single w/storm	10
4. Low-e Glass	16	11	11	Low-e	22
5. Add ½ in. exterior foam board	19	11	11	Single w/storm	22
6. Add 1 in. exterior foam board	17	11	11	Single w/storm	22

In the northern, colder zones, the thermal bridging effects are even more pronounced requiring more ambitious design changes. Example scenarios for Thermal Zone II changes are provide on Table 3-8.

[5] All homes have Uo-value of approximately 0.116

Table 3-8 Alternatives for achieving Equivalent Thermal Performance for Wood and Cold-formed Steel Framed Homes in HUD Thermal Zone II

Thermal Package Description[6]	Ceiling insulation	Wall insulation	Floor insulation	Window type	Glass area (percent)
WOOD FRAMED HOME					
Basic Wood Frame Design	19	11	11	Single w/storm	17
COLD-FORMED STEEL FRAMED HOME					
1. Increased insulation (1)	27	11	19	Single w/storm	17
2. Increased insulation (2)	32	19	11	Single w/storm	17
3. Reduce glass area	27	11	11	Single w/storm	10
4. Low-e glass	19	11	11	Low-e	9
5. Low-e glass	30	11	11	Low-e	17
6. Add ½ in. exterior foam board	21	11	19	Single w/storm	17
7. Add 1 in. exterior foam board	28	11	11	Single w/storm	17

Assumptions:

1. The floor calculations are intended only for a "clear" section. The factors in the table were derived from a simple attic assembly (sheathing on the bottom) with a single truss support. It is unknown how the heat transfer will be affected for floors, which are in the "sheathing-up" orientation.
2. The current ceiling design for this analysis calls for eight webbing member, cathedral style truss system to connect from the top chord to the bottom chord. The best data available was for a flat ceiling with two web members.
3. No metal plates are considered in the correction factor tables. Metal stabilizer plates called for in the assemblies further reduce the confidence in using these methods.
4. The effect of eave edges and connections, such as at the marriage line have not been well considered in this analysis. The attachment methods may increase heat transfer.
5. Attachment to the structural steel chassis may have a significant effect on the heat transfer through the floor joists.
6. It may not be valid to treat the midsection and outrigger floor sections as separate heat paths. In reality heat will migrate along the joists into the more conductive outrigger section.
7. Foam board used in the analysis is Expanded Polystyrene R-3.85 per inch. Extruded polystyrene can also be used which has a value of R-5 per inch.

[6] All homes have U_o-value of approximately 0.096

4

COST ANALYSIS

Methodology and limits of the analysis

For a building system that is never seen by the homebuyer, decisions about the structural frame – assuming comparable performance and market acceptance – are mainly predicated on cost. It is generally accepted that for cold-formed steel to take market share the cost must be competitive with, or less than, wood framing.

Demonstrating pricing equivalence or even comparable costs between the two materials is one of the major objectives of this research. This study assessed the first costs of wood compared to cold formed steel and compared on this basis the two materials were quite close. This is a particularly encouraging result given that the industry has invested considerable sums in the value engineering of only wood frame systems. The current manufactured housing system is literally and figuratively built on a wood-framing platform. The same comment can be made about the site building industry and, yet, steel framing has begun to make inroads into that segment of the building industry, albeit the criteria and conditions for acceptance are in many ways different from HUD-code housing.

The hard cost of cold formed steel framing compared with wood consists of three main elements: the material cost differences for a design that achieve roughly equivalent structural performance (the topic of the current research), the impact on labor (production speed, training, quality control and related factors) and other production-related considerations (equipment capitalization, material storage, handling, flow, waste disposal, etc.). (In addition, there are soft costs such as the expense in educating customers about the value of cold-formed steel versus wood.)

The research effort was organized in such a manner as to tackle these areas in sequence, looking first at the relative material costs for the two framing systems. The danger in this approach is the tendency to draw conclusions based on partial information; for example, relative material costs reveal little about the economics of changes in production. However, by demonstrating that the material costs are nearly equivalent, this work takes an important step in demonstrating the viability of steel framing for HUD code housing. Clearly more will be understood about the relative economics as work progresses and cost is a fertile area for further investigation.

Among the limiting parameters of this preliminary cost analysis are the following:

- The design was developed to meet the HUD standard requirements for Wind Zone 1 and Thermal Zone 1. Both conditions are the least restrictive and most HUD-code homes are sold in the area characterized by the confluence of these conditions. Given the thermal bridging issues discussed in Section 4, using steel framing in colder climates will represent a greater challenge.
- One home size was used for the analysis, a double wide home with frame dimensions of 28 x 56 ft. The design and analysis results for other configurations, notably single sections and larger homes, might require considerable changes impacting relative framing costs.
- The conditions placed on the design process did not give sufficient latitude to develop a design that takes advantage of the properties of steel. The major concession was the use of 24 in. on center framing compared to the industry standard of 16 in. on center wood framing. More exotic

designs using steel in creative and cost efficient ways with the potential of significant cost savings in a goal for future research.

- The design was developed from an industry "standard" configuration. Among manufacturers there are differences in fabrication techniques and structural design. Therefore, for any single company, the prototype might be more or less costly than current practice.

However, the value of the cost presented here should not be underestimated. Before this effort was initiated, there was little basis for understanding how the use of steel might impact construction costs, design and manufacturing. Many in the industry expected that since steel had not gained market share it would not fair well when compared on a material cost basis with wood. In fact, at current pricing, the material costs for steel and wood are quite close. The current work is an important first step upon which to build and the cost estimates contained in this section a starting point for more detailed analysis.

Toward a Valued Engineered and Cost Optimized Design

In mid-2000, the project Steering Committee reviewed an initial design for the structural components proposed by Anderson-Peyton. Using average industry values for wood framing costs, and estimated per pound cost for cold-formed steel, an initial cost comparison was made. As summarized in the last two columns of Table 4-1, the steel design represented an increase in cost of over $500 compared with a comparable wood frame home. Despite the higher cost, the Committee was encouraged by the results both because the wood frame design had evolved over the years to a near optimum configuration and the Committee recognized that there was ready opportunity to improve on the steel design. To explore the potential of this second point, the Committee established a project subgroup that was assigned the task of value engineering this first-cut design.

The subgroup took a narrow approach to optimization, considering only material and design changes that could be validated by engineering analysis. Taking advantage of the performance nature of the Federal Manufactured Housing Construction and Safety Standards requirements, the subgroup developed a far less expensive structural system that, strictly from a material cost standpoint, represented a cost reduction of $741 compared with the initial design and an estimated $222 savings over wood framing[7].

The sphere of analysis by this subgroup, however, was limited to the structural frame. To round out this cost comparison, several additional price components must be added including the following:

- The prototype design calls for outriggers or cross members spaced at 96 in. on center. A wood framed home of the same dimensions in lowest wind and snow load areas might be built without outriggers.
- With a 24 in. on center floor joist spacing, decking might need to be 23/32 in. versus 19/32 in. for a 16 in. on center wood frame design.
- As noted in the prior section on thermal performance, to compensate for the thermal bridging associated with steel framing, insulation levels would need to be increased. In the example shown on Table 3-7, ceiling insulation would be increased to R-22 from R-11.

Taking these factors into account would cumulatively add about $500 to the total cost of the steel framed home compared with the wood frame design. Subtracting out the $222 savings in the cost of the structural system yields a net cost of materials for the steel design of about $278.

Despite the many caveats that accompany this rough estimate of costs, this is an extremely encouraging result for several reasons, including the following:

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[7] Cost figures for the wood framing were based on industry average figures.

- The difference in cost is less than 10 percent of the components considered in the analysis and a fraction of the total cost for all the materials in the home. The cost difference of other factors, such as manufacturing, warehousing and labor, are expected to be much larger and have a more profound impact on the cost comparison.
- The subgroup spent only a few months developing the value-engineered solution. With additional time and resources, further cost reductions can be expected.
- Several suggestions for cost savings were not considered, as they would have required testing or other types of evaluations beyond the resources of the project to validate. The improvements are slated for subsequent phases and are discussed in Appendix E.
- Due to time and resource limitations, the subgroup was unable to take advantage of the expertise possessed by the steel fabricators. Further, the subgroup did not consider proprietary products, an option that a manufacturer investigating the technology would certainly consider.
- The current work considered fully replacing the wood frame with cold-formed steel. The relative economics might be improved by considering the use of steel for only one or two subcomponents, such as floors or interior walls. As evident from the results on Table 4-1, trusses are the one area where wood frame continues to hold a first cost advantage (albeit, at a cost difference of $15, the cost differential is modest). A hybrid design using steel for the floor and walls and wood for the ceiling may be a least cost approach and should be the subject of future investigation.

It was the primary goal of this phase to establish that, strictly on the basis of first cost, steel could be competitive with wood framing. This result suggests that cold-formed steel framing should indeed be given serious consideration by home manufacturers. However, the Committee is cognizant of the fact that to measure the real cost of the technology other factors must be considered and addressed by subsequent research and analysis. A partial list of these factors includes the following:

- Costs associated with plant retooling to use steel components (tools for applying connectors, stud extruders, etc.)
- Costs associated with labor retraining
- Costs associated with inventorying steel frame parts
- Savings associated with less material wastage
- Costs or savings changes in manufacturing processes (will steel speed or slow production?)

As noted elsewhere in this report, using steel for only a part of the structural framework appears to have considerable merit.

Table 4-1 summarizes the cost comparison of wood with steel framing. The table divides cost by building component. The three columns at the far left of the table provide the cost information for the three cases examined: the value engineering steel design (as defined in Appendix B), the wood framed home, and the steel design prior to the value engineering analysis. Prior to value engineering, the steel home had a material cost of about $3,000. Value engineering brought the cost down to about $2,258, less than the reference wood framed home cost of $2,480.

Table 4-1 Comparison of costs (Cold-formed steel versus wood) for the structural system only

Use	Unit weight (lb/ft)	Quantity	Length	Total length	Total weight	Price (at $0.38/lb.)	Value engineered steel design	Wood framing	Initial steel design
Floor system									
Joists	1.52	68	13.5	918.0	1,395.4	$530.24			
Joists Ext.	1.52	24	2.0	48.0	73.0	$27.72			
Rim Track	1.73	4	56.0	224.0	387.5	$147.26			
Web Stiffeners	1.06	108	0.8	81.0	85.9	$32.63			
					1,941.7		**$738**	**$800**	**$938**
Exterior walls									
Studs sides	0.72	62	7.5	465.0	335.7	$127.58			
Studs ends	0.72	30	8.4	252.0	181.9	$69.14			
Studs Pony	0.41	30	1.3	39.0	16.0	$6.08			
Track at sides	0.63	4	56.0	224.0	141.1	$53.63			
Track at ends	0.63	4	56.0	224.0	141.1	$53.63		See note 1	
Track at pony walls	0.47	8	13.7	109.6	51.7	$19.66			
Track at openings	0.63	19	6.0	114.0	71.8	$27.29			
Headers	1.09	26	3.5	91.0	99.6	$37.83			
					1,039.0		**$395**	**$450**	**$518**
Interior walls									
Studs Mating	0.62	54	9.4	507.6	314.7	$119.59			
Studs	0.42	60	9.4	564.0	236.9	$90.01		See note 2	
Studs	0.48	2	120.0	240.0	114.7	$43.59			
Track	0.37	30	10.0	300.0	111.0	$42.18			
Track Mating	0.53	2	31.0	62.0	32.9	$12.49			
					810.2		**$308**	**$480**	**$397**
Roof trusses									
Top Chord	0.62	54	13.7	739.8	460.7	$174.86			
Bottom Chord	0.62	54	13.4	725.2	451.1	$171.41			
Web 1	0.62	54	0.6	33.6	20.9	$7.95			
Web 2	0.62	54	3.6	199.3	123.9	$47.10			
Web 3	0.62	54	0.9	50.8	31.6	$12.00			
Web 4	0.62	54	3.5	193.9	120.6	$45.82		See note 3	
Web 5	0.62	54	1.3	70.7	44.0	$16.72			
Web 6	0.62	54	3.6	196.0	122.0	$46.33			
Web 7	0.62	54	1.6	90.2	56.1	$21.31			
Web 8	0.62	54	3.6	194.4	121.0	$45.95			
Web 9	0.62	54	2.0	108.0	67.0	$25.44			
Subtotals (No truss on gable ends therefore 54 trusses total)							**$615**	**$600**	**$943**
Other items									
Mating wall beam	3.81	2	56.0	112.0	426.7	$162.15			
Ridge cap	0.92	1	56.0	56.0	51.5	$19.58			
Truss caps	0.49	2	56.0	112.0	54.9	$20.85			
Subtotals					**533.1**		**$203**	**$150**	**$203**
Total weight (lbs.)					**5942.2**		**$2,258**	**$2,480**	**$2,999**
Cost difference versus value engineered steel							**$0**	**$222**	**$741**
Percent difference							**0.0**	**9.8**	**32.8**

Notes:

1. Cost figures are based on the design configuration included in Chapter 2 of this report
2. Steel floor framing figured at 24 in. on center, lumber at 16 in. on center
3. Steel exterior wall studs figured at 24 in. on center, lumber at 16 in. on center
4. Steel mating wall studs figured at 24 in. on center, lumber at 16 in. on center
5. Steel mating wall beam figured continuous, lumber beam figured at open, with remainder using 2 x 3 in. belt rail.

5

NEXT STEPS

The completed project was a major step toward answering two important questions about the feasibility of using steel framing in the home manufacturing environment: can a cold-formed steel design be developed that is approvable under the HUD standards through the traditional DAPIA review process; and, can such a design be cost competitive with wood framing on a first cost basis. The completed work focused mainly on the structural issues and described remaining work required to develop a cost effective and approvable thermal solution.

The research also left important technical questions unanswered that subsequent study will be designed to address. Among the issues that will shape future research are the following:

- How can cold-formed steel be otherwise integrated into the manufacturing process? On the surface it appears that a material that is light, dimensionally stable and generates almost no wastage would be ideal for the manufacturing environment. Manufacturing process engineering is needed to suggest strategies for capturing these advantages and modifying plant production in ways that take advantage of inherent properties of cold-formed steel framing. Future study will need to consider retraining of workers, inventory maintenance, material movement, speed of production and related factors.
- How will steel impact the economics of manufacturing homes? First cost is only one of the factors that contribute to the total cost of moving from wood to steel framing. Using steel cost efficiently may require new equipment (e.g., stud extruders, new fasteners and fastening equipment) and associated recurring expense (e.g., maintenance) that must be capitalized, changes in production flow (as noted above) that have the potential to impact production rate, plant fit out to accommodate changes in production flow and related start up costs (e.g., labor training). The aggregate of all of these major cost contributors will dictate the real economics of cold-formed steel technology.
- Can steel framing overcome the barriers to market entry often associated with new materials and technologies? In some markets, notably California, cold-formed steel has already gained a toehold in the housing market. Manufactured housing is in many ways an easier market to penetrate if the economic advantage of the material can be clearly demonstrated. Several manufacturers have experimented with steel suggesting that customer acceptance – as noted earlier, homebuyers are notoriously conservative in their approach to housing choices – is not viewed as an insurmountable stumbling block.
- Can steel framing be made more manufactured home friendly? While there are many apparent advantages to manufacturers that switch to steel for framing, only small steps have been taken to thoroughly take advantage of the promise. For example, home manufacturing relies on rapid production rates and use of semiskilled labor. Yet, the primary methods for connecting steel elements are relatively slow (e. g., screws). New technologies on the horizon, such as clinching technologies, will need to be refined if steel is to move forward as an attractive alternative to wood.

The role of MHRA is to assist industry in addressing the former areas of investigation – evaluating and developing new technologies – and to share research results with the industry at large. Clearly, in regard to steel framing, there are broad technical challenges that are within MHRA's sphere of operations to work on with industry: the current research covered important ground but more work needs to be done before industry can be expected to carry the technology into commercialization. (A summary of the tasks for carrying this work forward are presented in Appendix C).

In examining the opportunities to move forward on cold-formed steel framing, two approaches were considered. First, continue working on technical issues of a generic nature refining the prototype design and investigating critical ancillary issues, such as steel frame friendly manufacturing processes. This would be a continuation of the direction followed in the prior work reported in this document. Or, second, work with individual manufacturers on specific applications of the technology and allow the company-specific interests to drive the direction of the research and scope of tasks. Research in either approach might cover the same ground but in the latter case, the manufacturer's bias in terms of application of the technology is the driver in defining the scope and approach to tasks. In either case, the results will be made available to the industry at large.

A general consensus of the companies that have expressed an interest in the technology is to pursue the latter approach. The merits of this approach include the fact that it is much more likely to lead to commercialization since the cooperating manufacturer will have identified the market opportunity beforehand and, by a willingness to commit resources, the internal support needed to move the technology forward. The trade-off for the pioneering manufacturers is the lead time in bringing a new method to market. Since the results will be shared with industry, the competitive advantage will have a limited life span.