

**Theoretical Analysis of Light-Weight Truss Construction in Fire Conditions,
Including the Use of Fire Retardant Treated Wood**

by

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A Thesis

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Master of Science

in

Fire Protection Engineering

by

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May 4, 2006

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Abstract

Fire statistics suggest that there is an urgent need for improved performance of light-weight truss construction in fire scenarios. This thesis proposes the use of Fire Retardant Treated Wood (FRTW). Several floor truss systems were designed for a residential living room using sawn lumber and FRTW. A finite difference, heat transfer model was used to determine time to collapse and to identify modes of failure during a simulated exposure to the standard ASTM E-119 test fire curve. As part of ongoing research at WPI, this is an initial effort to use analytical methods in the study of heat transfer and structural performance of wood construction during fire conditions. Results were examined for important relationships to further advance the understanding of collapse mechanisms in wood trusses. Experimental procedures for further testing have also been developed. Acknowledgment that in-service conditions may alter structural fire performance is made and the implications are discussed. An alternate fire scenario, more representative of residential fire loading, was also developed and compared to the ASTM E-119 fire curve.

Acknowledgments

I would like to acknowledge the participants of this project. These people have intimately helped in its development, and deserve credit for the project's success, as well as my sincere gratitude.

Project Co-Advisor: Professor Robert W. Fitzgerald

Research Assistant: Donald Benanti

Special Thanks to:

Project Major Advisor: Professor Leonard D. Albano

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1.0 Introduction

Light timber construction was a great advancement in modern construction practices. It saves money, time, and materials while maintaining structural integrity. In recent years however, it has become evident that light timber construction performs poorly in fire conditions and is prone to early collapse. This presents a particular hazard for emergency responders, especially firefighters, who many times must enter these dwellings to extinguish the blaze.

Advancements in fire protection engineering have brought about a new generation of Fire Retardant Treated Wood (FRTW), chemically impregnated sawn lumber designed to retard and eventually cease the process of pyrolysis via chemical intervention in the release of combustion reactants. But problems with the structural integrity of these materials arise when exposed to long durations of high service temperatures or high moisture conditions. However, new chemical treatment formulations and the fact that most commercial FRTW products are now specified to be used only indoors are helping to increase the functionality of this material.

The main goal of this project is to explore possible failure modes of trusses under fire loads when designed using regular sawn lumber and metal connecting plates, and then to extrapolate those findings to predict the performance of FRTW in light weight truss construction. In order to achieve this, several problems were addressed. The first problem was to conduct extensive library research on FRTW and factors affecting its strength, followed by research of common residential fire scenarios and to model a similar assumed situation using zone model software. Five different trusses were

designed using typical loadings for residential living spaces and the two most economical of these were used for further analysis.

The next problem was to develop a theoretical heat transfer model to determine the thermal profile within a wood member and steel plate that would incorporate char formation and changing thermophysical properties of wood during exposure. A finite difference model was created using conservation of energy. Empirical thermal degradation models for both steel and wood were researched, and a model that describes how FRTW will degrade during exposure was created. By establishing temperatures of the materials at any given time using the model, the amount of charring in the wood section and thermal degradation of strength properties in the wood and steel connecting plates are determined using the empirical and derived formulas.

It is hypothesized that the connector plates would be the primary location of catastrophic failure; therefore, focus of this project is directed towards the interface between the wood and the metal teeth that are used to secure each joint. The plates were modeled to transfer load by the teeth alone, and each tooth was evaluated as a uniformly loaded cantilever beam with variable section properties.

Expected failure modes can be described via three mechanisms. The first would be simple mechanical failure of a wood section from a combined effect of charring and thermal strength degradation. The second, a simple mechanical failure of the truss plate from reduced strength due to increased temperature. The third mode would be the most complicated and is described as tooth withdrawal or “peeling” where the metal plate pulls out of the wood member in the same direction in was inserted.

Finally, future testing methods are developed to determine the thermal properties of FRTW, to evaluate FRTW char formation, and to determine better the characteristics of the interaction between truss plates and wood members in normal and fire scenarios with the goal of enabling a more comprehensive evaluation of this topic.

2.0 Literature Review

Many statistics and publications portray the dangers of light timber construction to the public and to emergency responders. This chapter is intended to give the reader a sense of the proportion of this problem.

Also described in this chapter are the chemical behavior of FRTW and how codes and standards have been developed to deal with this high potential, though challenging, material.

This chapter will then describe the background work that was necessary to investigate FRTW as an option in light-weight truss construction. Computer models and structural designs were developed to simulate a typical structural fire environment that may be found in the living room of a residential home.

2.1 Firefighting and the Dangers of Structural Collapse

Fire Statistics

In a scientific study conducted by the Federal Emergency Management Agency (FEMA) entitled *Trends in Firefighter Fatalities Due to Structural Collapse, 1979-2002*, it was found that firefighter deaths in residential buildings have more than tripled in the last decade compared to the previous decades (1994-2002: 33 deaths; 1983-1992: 9 deaths) (Brassal, Evans 2002). Moreover, in a FEMA study entitled *Wood Truss Roof Collapse Claims Two Firefighters Memphis, Tennessee*, researchers express that awareness and concern about the hazards of lightweight construction need to be increased throughout the Fire Service (Routly 1992). Even if a building is defined as “fire-resistive” by the building codes, this does not guarantee it will survive a fire or the fire fighting effort (Brannigan 1992).

Structural Integrity

The way that buildings are constructed using wood has changed significantly since the beginning of the 20th century. Timber construction was typically done using members with very large cross sections with the minimum dimension somewhere between six and ten inches, and is now known as “Heavy Timber” construction. Because it requires significant cost and effort to construct (e.g. lifting these large beams require machinery), and building materials are becoming increasingly expensive, it is no longer economically feasible to construct timber structures in this way (*Reading a ...2004*). Efficient and cost-effective methods of construction are increasingly prevalent; unfortunately they are more prone to collapse in the event of a fire. Light-weight construction materials and methods are praised by the building industry as the answer to affordable housing in this country. State and independent building codes set minimum requirements for load-carrying capacity, fire resistance, and spans lengths in order to maintain a minimum level of safety, yet the dangers of lightweight construction are still real and ever present to the Fire Service (Brannigan 1992).

Because wood is a combustible material, when it burns, there will be a certain mass loss rate associated with the combustion and over time, cross-sectional areas of burning members will decrease therefore decreasing their structural strength and integrity. Though light timber construction saves the industry money by allowing the use of smaller, less expensive members, when exposed to fire conditions, these smaller members heat up, and are consumed more rapidly and after a relatively short period of time are unable to carry the loads for which they were designed.

The vast majority of structural fires are fought by firefighters standing on or under wooden structures (Brannigan 1992). Because occupant evacuation is the first objective

for the fire department, very few civilians are killed by burning building collapse. Unfortunately, firefighters are typically involved with a burning building when it has been weakened by flames and is close to the point of collapse. The fire endurance characteristics of lightweight construction systems have been discussed and debated among scholars and within the Fire Service for years. The actual time to collapse, and the presence or absence of warning signs prior to collapse, are of great interest to the Fire Service (Dunn 1988).

Recent testing was done by the National Institute of Standards and Technology (NIST) in association with the Phoenix Fire Department to demonstrate time to collapse of residential roof truss construction. Typical times were around 20 minutes from the time of ignition and few if any warning signs were evident before the final collapse. The suddenness of the failures is one of the most harrowing details to firefighters (Bukowski 2002).

Building codes often require 1 or 2 hour fire resistance ratings for floors and load bearing structures in commercial occupancies, but are almost never required in residential buildings. Even though two hours is expected to be more than adequate for evacuation, smoke obscuration and being in unfamiliar buildings are only two of the unpredictable variables that can increase the time firefighters will spend in the structure. Also, fire resistance ratings are only a benchmark developed under standard furnace test exposures which are often times much less severe than natural fires, making this rating highly unrepresentative of their actual ability to maintain integrity (Bukowski 2002). Further discussion of building code requirements can be found in Section 2.3 Codes and Standards for FRTW.

2.2 Overview of FRTW

This section is intended to provide the reader with a brief history of how FRTW has been used and some issues that have arisen while using it. Also discussed is the chemical means by which FRTW works to inhibit sustained combustion and how this chemical treatment affects its structural performance.

History of FRTW

In the 1980's, when FRTW was used commonly for roof sheathing, it was discovered that these materials are extremely prone to strength degradation when exposed to a natural environment. Under the correct conditions the chemicals used in treatment would prematurely activate and begin to lower the temperature at which thermal degradation would occur, effectively increasing char and reducing the production of flammable volatiles. However, over time this process would affect the entire section of the wood element and cause a reduction in strength. The wood would darken and become very brittle. In the worst cases, entire roofs needed to be replaced. The service life of the early FRTW roof sheathing was anywhere from 3 to 8 years. Since this occurred on the roofs of many structures, these problems were very visible in nature and quickly made the industry aware that something was having serious negative effects on the service life of FRTW and soon led to many studies on the types of factors that caused its deterioration. (LeVan, Collet 1989)

Chemistry of FR Treatment and Strength Degradation

All FR systems use phosphorus nitrogen or boron, and most have phosphorus as the central element in the form of phosphoric acid. When wood reaches a temperature of 260°C, cellulose begins to break down and produce tars and flammable volatiles. Cellulose is the primary contributor to the production of such volatiles and its

decomposition can be accelerated when in the presence of water, acids, and oxygen. The primary reaction in this decomposition is depolymerization caused by the cleavage of glycosidic linkages which is essentially the process of hydrolysis. In the presence of very strong acids hydrolysis can occur at room temperatures. Susan L. LeVan and Jerrold E. Winandy of the Forest Products Laboratory (FPL) explained the most widely agreed upon theory of how the acids actually act as FR chemicals in their 1990 publication entitled “Effects of Fire Retardant Treatments on Wood Strength: A Review”:

Acids can catalyze the dehydration of a glucose unit by addition of a proton to the oxygen atom of a hydroxyl group, resulting in formation of the unstable carbonium ion. The carbonium ion rearranges and regenerates the proton, thereby propagating the process... The glycosidic linkages can also undergo attack from a proton, resulting in depolymerization of polysaccharide chains. The proton forms a conjugate acid with the glycosidic oxygen. The C-O bond is cleaved to form an intermediate cyclic carbonium cation, which initiates addition of a water molecule, resulting in a stable end product and release of the proton.

In short, this reaction in the presence of strong acids decomposes the cellulose quicker than usual (increasing the char), and releases less volatiles and more stable molecules such as water so that flaming combustion is severely impeded. Flame spread is also decreased dramatically via the same processes, creating less radiant feedback which diminishes the possibility of further continued combustion. (LeVan, Winandy 1990)

The effect of FR treatment at high temperatures has been found to be highly dependent on species. Thermal degradation of wood can be viewed as the sum of the degradation of its parts. Cellulose and hollocellulose make up 50 to 75% of wood, where hollocellulose is comprised of alpha-cellulose and hemicellulose, and lignin is the enzyme that acts as the glue to hold it all together. When each compound (excluding hemicellulose) was isolated and thermally degraded in nitrogen, it was found that hollocellulose most closely follows the degradation of actual wood member than any

other component separately. This allows for the conclusion that studying the thermal degradation of hollocellulose, and most specifically hemicellulose, would provide a close explanation on how wood will degrade in general. (LeVan, et al. 1990)

Xylan is a main component in the hemicellulose of hardwoods and is the least thermally stable hemicellulose since pentosans (xylan) are very susceptible to dehydration reactions. Softwood hemicellulose is low in xylan and high in a more stable molecule called galactoglucomannan. Since FR chemicals are effective by increasing the rate of hydrolysis, hardwoods are more negatively affected by the treatment than softwoods, and it is for this reason that today, all commercially available FRTW is created using softwood species. (LeVan, et al. 1990)

Other research funded by FPL confirms the hypothesis that hemicellulose plays an important role in determining the strength of FRTW. In this particular study, Winandy et al determined the percentage of certain types of cellulose and hemicellulose that are integral in the determination of mechanical strength, then treated the specimens with monoammonium phosphate (MAP). One group of specimens was exposed to 27°C for 560 days and then tested for their residual percentages of cellulose and hemicellulose while the other was tested immediately after treatment to act as the control. The conclusions state that the degree of polymerization of cellulose did not appear to be related to strength loss under thermal degradation but the amount of hemicelluloses left undamaged after treating, especially the mannans in galactoglucomannan, were highly related to residual modulus of rupture (MOR) and work to maximum load (WML). (Sweet, Winandy 1999)

Since the concern for strength loss in FRTW originated from observations while in service, the idea that cyclic temperature exposures and in-service changes in moisture

content (MC) could have been contributing factors was also investigated. Untreated specimens and those treated with MAP were exposed to cyclic 65°C temperatures at 7 hours per day and at 3.5 hours per day, with a control group at a constant 65°C. Exposure times ranged from 0 to 215 days with intermediaries at 21, 60, and 160 days. Two target MC levels were used: 6 and 12 percent. Below, Table 1 shows the slope of the trendlines of the best fit to all data.

Table 1: Comparison of cyclic temperature with constant temperature (LeVan et al. 1996)

Specimens	MOR slope		
	Cyclic at 65°C ^a		Constant at 65°C
	7-hr/day	3.5 hr./day	
MAP	-0.097	-0.194	-0.171
Untreated	-0.043	-0.086	-0.002

^a Slope from regression line using all data points.

Modulus of elasticity (MOE) values were relatively unchanged while Table 1 shows that MOR exhibited a slight negative slope. This data suggests that cyclic temperature exposure cannot be said to be more severe than constant exposure. Other data from this research showed that treated materials had a greater tendency for degradation than untreated as was the trend exhibited in past experiments. There was also a slight decrease in strength from 6% MC to 12% MC, but strength loss due to increase in MC was no different than that exhibited by untreated lumber. (LeVan et al. 1996)

Further work at the FPL showed the correlation between relative humidity (RH) and strength loss. Untreated and MAP treated plywood specimens were subjected to exposures of various combinations of temperature and RH. Their results are summarized in Figure 1 and Figure 2 below. It was concluded that as RH increased, the rate of strength loss at elevated temperatures also increased. However, the effect of RH did not appear to be as influential as that of the temperature exposure. (Winandy et al. 1991)

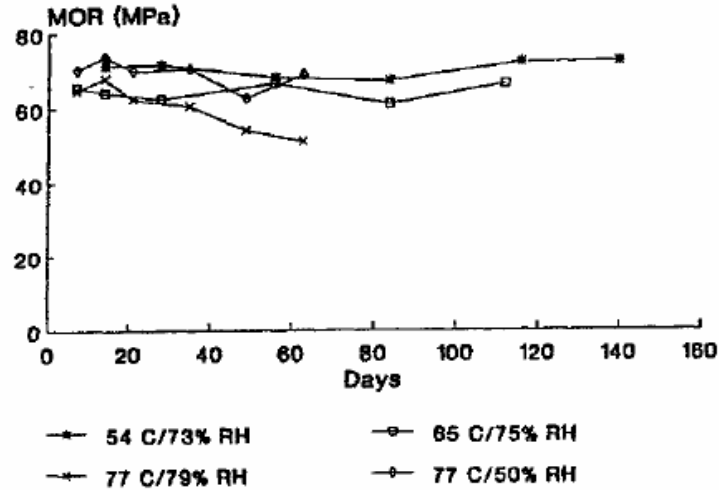


Figure 1: Effect of exposure to various RH and temperatures on MOR of untreated plywood (Winandy et al. 1991)

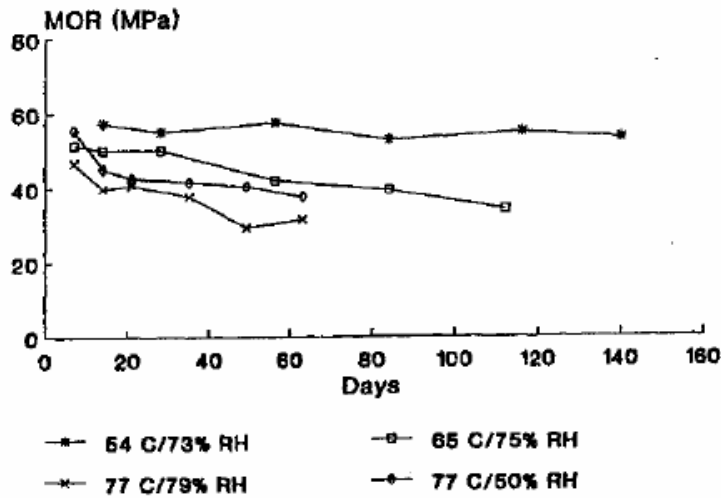


Figure 2: Effect of exposure to various RH and temperatures on MOR of MAP treated plywood (Winandy et al. 1991)

Grade and thickness was also investigated as a possible variable in the effects of FR treatments. One study used two thicknesses and three commercial grades of southern pine plywood as well as defect-free N-grade veneer plywood, all treated with MAP to determine the trend. Each specimen was subjected to an exposure of 66°C and 75% RH for either 30, 60, or 90 days and then tested for MOR, WML, and MOE. Results showed that strength loss from treatment, re-drying, and subsequent high temperature exposure

was dependent on neither quality nor grade of the plywood. Initially the thinner materials seemed to degrade more severely but when results were adjusted to reflect the volume of wood affected it was found that thickness as well had no intrinsic effect on the development of strength loss. (Lebow, Winandy 1998)

Essentially all FR treatments cause large, rapid decreases in pH, first because the solutions themselves are usually acidic, and second because decomposition reactions in wood release acetic acid (LeVan et al. 1990). By this reasoning, the possibility that wood pH could be used as a predictor of strength loss was examined as well. A strong relationship was noted between changes in pH of the tested plywood specimens and the reductions in strength and energy properties. Figure 3 below summarizes some of the data collected from these experiments. The key in the figures shows the number of days that each specimen was exposed to 66°C (150°F) and 75% RH. As seen in the data, as temperatures increase, the differences in pH resulting from the initial re-drying after treatment becomes insignificant after extended periods of exposure. In other data collected, it was determined that the additions of borate compounds produced a significant buffering effect that slowed or lessened the decreases in pH. (Lebow et al. 1999)

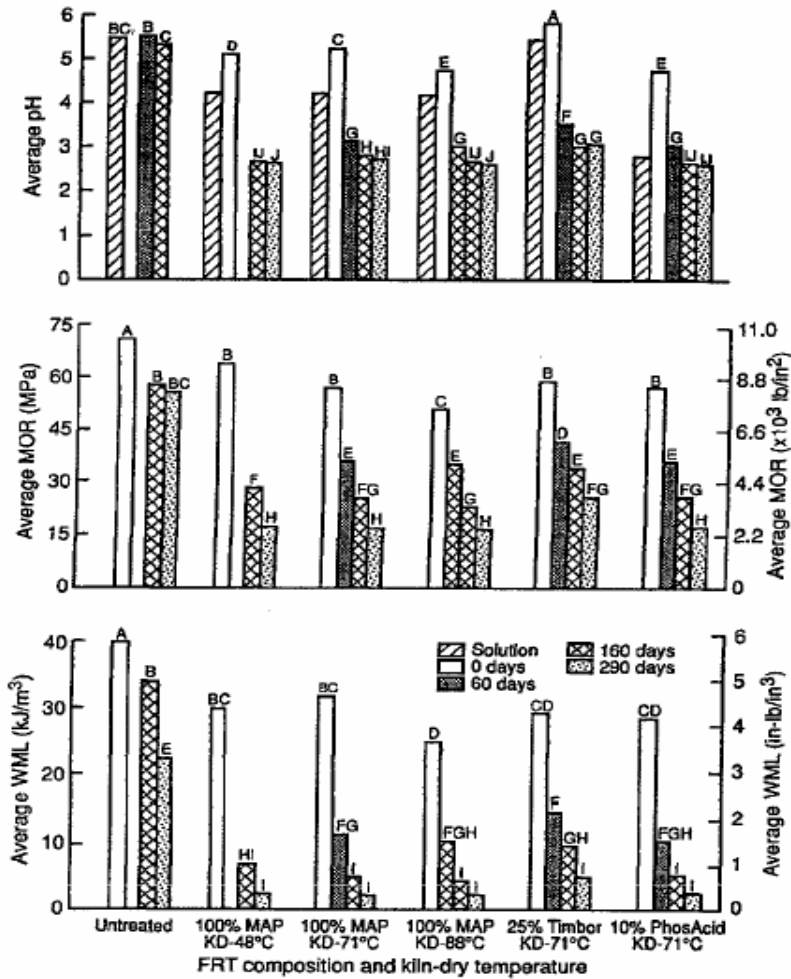


Figure 3: Effects of various FR formulations and re-dry temperatures on pH, MOR, and WML (Lebow et al. 1999)

Because kiln drying is by far the number one method used to cure softwood dimension lumber, the effects of kiln drying were independently examined as a possible contributor to overall strength loss. Table 2 below shows the difference in the effects of using a re-dry temperature of 60°C as compared to that of 110°C. The table shows a dramatic decrease in mechanical properties as the re-dry temperature increases. This is attributed to the fact that when exposed to temperatures above the boiling point of water, generally referred to as high temperature drying (HTD), hydrolysis is catalyzed even

more than is expected from treatment alone, severely increasing the production of acid in the system and therefore increasing the rate of strength loss. (LeVan et al. 1990)

Table 2: Effects of re-dry temperature on mechanical properties of various FR treated plywood specimens. The change in mechanical properties was as compared to untreated control specimens. (LeVan, Winandy 1990)

Chemical ^a	Species	Redry temperature (C)	Change in mechanical property (%) ^a			
			MOR	MOE	Energy	C-par
Borax	DF-Ply	60	-23		-34	--
MIN			-27		-25	--
PYR			-14		-30	--
FRT			-24		-36	--
CZC			-21		-41	--
Borax	DF-Ply	110	-34		-68	--
MIN			-25		-50	--
PYR			-30		-57	--
FRT			-36		-64	--
CZC			-41		-64	--

2.3 Codes and Standards for FRTW

Much of the research described in the previous section resulted in the formation of standard test methods for the evaluation of effects of FR treatments and the final strength properties of FRTW. This also led to the inclusion of FRTW into developing building codes.

The American Society for Testing and Materials (ASTM) has developed numerous methods for quantifying the effects of various in-service conditions on strength properties of FRTW. Building code officials often require that these tests be performed in order to certify that a particular manufacturer's product is of sufficient quality to be used as construction materials.

The purpose of this section is to make the reader aware of some of issues regarding FRTW that have been addressed by the professional public.

ASTM D 5664-02

This test method is for the evaluation of the effects of FR treatments and elevated temperatures on strength properties of FRTW. The general objectives for this test are to develop data to adjust allowable design stresses of sawn lumber for the initial effects of treating with any FR formulation and to develop data for in-service thermal stability up to $66 \pm 2^{\circ}\text{C}$ ($150 \pm 4^{\circ}\text{F}$) and $\geq 50\%$ RH. This test was created so that all manufacturers of FRTW can evaluate their products in an effort to maintain the expected level of structural performance.

There are two test procedures with a third optional test for size effects. The first two procedures use small clear specimens cut from end-matched nominal 2 x 4 dimension lumber. Procedure 1 compares initial effects of FR treatments to untreated controls for bending, tension parallel, compression parallel, and horizontal shear properties. Procedure 2 assesses differential trends between the treated and untreated specimens for bending and tension parallel properties with prolonged high temperature exposures. Below in Figure 4 is an example of a cutting pattern to obtain specimens for each type of test. The optional Procedure 3 uses a full-size nominal 2 x 4 to modify the results from Procedures 1 and 2. Table 3 and Table 4 below summarize the testing when using Procedure 1 or Procedure 2.

Table 3: Summary of Procedure 1 for the ASTM D5664 test

Procedure 1			
<u>Step</u>	<u>Description/Requirements</u>	<u>Limit Value</u>	<u>Method</u>
Chemical Treatment	Flame Spread Index ≤ 25	10min	ASTM E84
	No significant combustion	20min	-
	No flame spread past 10.5 feet from center of burners	30min	-
	Treatment Report	-	-
Post-Treatment Drying	Moisture Content	$\leq 19\%$	Manufacturer Designated
	Re-dry temperature, first day	(-)2° tolerance	
	Re-dry duration, first day	21hrs	
	Re-dry temperature, first day	(-)3° tolerance	
	Re-dry duration, first day	Remainder	
Equilibration	Constant Weight	22+5°C	-
	Relative Humidity	65+1%	-
Testing	Bending, Compression Parallel, Horizontal Shear	Failure	ASTM D143
	Tension Parallel	Failure	ASTM D3500

Table 4: Summary of Procedure 2 for the ASTM D5664 test

Procedure 2			
<u>Step</u>	<u>Description/Requirements</u>	<u>Limit Value</u>	<u>Method</u>
Chemical Treatment	see Procedure 1		
Post-Treatment Drying	see Procedure 1		
Exposure	3 groups of specimens unexposed	-	-
	3 groups exposed	66+2°C 50% RH	-
	Exposure duration 1	36+3days	-
	Exposure duration 2	72+3days	-
	Exposure duration 3	108+3days	-
Equilibration	see Procedure 1		
Testing	Bending	Failure	ASTM D143
	Tension Parallel	Failure	ASTM D3500

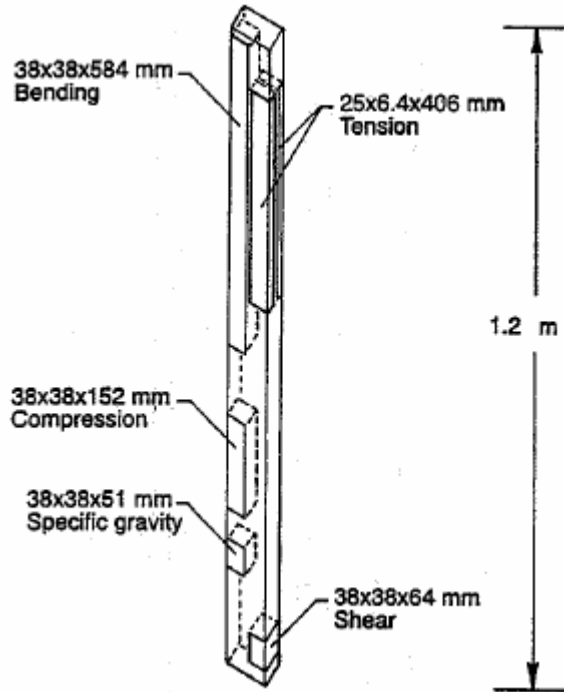


Figure 4: Hypothetical cutting pattern to obtain specimens for the ASTM D5664 test (ASTM International, Vol. 4.10 2004)

ASTM D 5664 calls for the treatment of the pieces so that the retention level using a particular agent would not be below midpoint of the retention range as specified for the species by the certifying agency. If standards other than AWPA C20 or NFPA 703 are to be met, retention level performance criteria shall be stated. All specimens shall be weighed before and after treatment to determine their solution retentions and a treatment report shall be completed with treating cycle, times, pressures, gage retentions, and piece retentions.

There is no upper limit on the re-drying temperature for this test and it is recommended that all pieces be stickered to allow proper flow over all surfaces and even drying. (ASTM International, Vol. 4.10 2004)

ASTM D 6841-03

ASTM D 6841 is the standard practice for calculating design value treatment adjustment factors for FRTW. This test uses results obtained from ASTM D 5664 and in conjunction with computer generated thermal distribution curves, allows the user to calculate design adjustment factors to be applied to published allowable stress values in order to capture the effects of treatment and service temperatures. This test ensures that structural engineers are able to effectively design using FRTW by compensating for these negative effects.

Some simple equations are used to determine the design factors. The first three equations are shown below and the variables are described in Table 5 below.

$$R_{ti} = a + k_t(D) \quad (1) \text{ (ASTM Int., Vol. 4.10 2004)}$$

$$k_{50} = k_t(50 / RH_i) \quad (2) \text{ (ASTM Int., Vol. 4.10 2004)}$$

$$\ln\left(\frac{k_{50}}{k_2}\right) = \frac{[E_a(T_1 - T_2)]}{R \cdot T_1 \cdot T_2} \quad (3) \text{ (ASTM Int., Vol. 4.10 2004)}$$

Table 5: Summary of variable for calculation of strength reduction design factors for FRTW

Equation 1		Equation 3	
Symbol	Description	Symbol	Description
R_{ti}	Ratio of average treated to untreated values	k_2	Strength loss rate at mean bin temperature
D	Number of days specimens exposed to elevated temperatures	E_a	21,810 cal/mol·°K
a	Intercept	R	1.987 cal/mol·°K
k_t	Slope, strength loss rate	T_1	Test temperature, °K
Equation 2		T_2	Bin mean temperature, °K
k_{50}	Strength loss rate at 50%RH		
RH_i	Elevated temperature test RH		

Equation (1) determines a regression line that describes the loss of strength over time. Equation (2) (ASTM Int., Vol. 4.10 2004) calibrates the strength loss rate for and RH to the strength loss rate at 50%RH. Equation (3) (ASTM Int., Vol. 4.10 2004) then calculates the strength loss rate per day.

Equation (4), shown below is the final equation in the process. This final equation uses the strength loss rate per day calculated from Equations (1), (2), and (3), and other values described in Table 6, to finally determine the treatment adjustment factor for particular species impregnated with a specific fire-retardant. (ASTM International, Vol. 4.10 2004)

$$TF = [1 - IT - n(CF)(CLT)] \quad (4) \text{ (ASTM Int., Vol. 4 2004)}$$

Table 6: Summary of variable for final equation for determining treatment adjustment factors for FRTW

Equation 4	
<u>Symbol</u>	<u>Description</u>
TF	Treatment adjustment factor = (1-IT)
IT	Initial treatment effect = (1-R _o)
n	Number of iterations = 50
CF	Cyclic loading factor = 0.6
CLT	Total annual capacity loss
R _o	Ratio of average treated to untreated values for unexposed specimens

ASTM D 3201-94(03)

ASTM D 3201 is the standard test method for hygroscopic properties of FRTW and wood based products. This test prescribes the procedure for determining the MC of FRTW samples after being exposed to a standard high relative humidity condition of 90±3%RH at 27±2°C (ASTM International, Vol. 4.10 2004). Data collected from this test allows engineers to suitably asses the impact of designing using FRTW in humid environments.

It is important to test the hygroscopic properties of FRTW because these products are particularly susceptible to retaining high levels of moisture, especially at high RH. This can cause staining, decay, poor paint adhesion, migration and excretion of chemicals, and even fastener corrosion. A summary of the testing procedures can be seen in Table 7.

Table 7: Summary of test procedures for ASTM D 3201, test for hygroscopic properties

Procedure	Value
Weigh each specimen	±0.2%
Expose specimens under constant RH and temperature	90±3%RH, 27±2°C
Maintain exposure atmosphere	7days
Weigh each specimen immediately after removal	±0.2%
Dry specimens in oven until constant weight is obtained	103±2°C
Re-weigh	±0.2%

Using Equation (6) (ASTM Int., Vol. 4.10 2004) and (5) (ASTM Int., Vol. 4.10 2004) below, MC before and after exposure is calculated, respectively. By finding the difference between these two values, and comparing this outcome for both untreated and treated lumber in the same conditions, the increase in MC due to treatment can be assessed. Variables in Equations (5) and (6) are found in Table 8. (ASTM Int., Vol. 4.10 2004)

$$MC\% = \frac{A - B}{B} \cdot 100 \quad (6) \text{ (ASTM Int., Vol. 4.10 2004)}$$

$$MC\% = \frac{C - B}{B} \cdot 100 \quad (5) \text{ (ASTM Int., Vol. 4.10 2004)}$$

Table 8: Summary of variable in equations used to determine severity of MC increase in treated lumber after exposure to high-humidity conditions per ASTM D3201

Symbol	Description
A	Weight prior to high-humidity exposure
B	Oven-dry weight
C	Weight after high-humidity exposure

ASTM D 2898-94(99)

ASTM D 2898 describes the standard test methods for accelerated weathering of FRTW for fire testing. These test procedures are important in determining the severity of the effects of leaching, drying, temperature, and if desired, ultraviolet light on different formulations of fire-retardant-treatments.

A summary of the testing methods is shown below in Table 9.

Table 9: Summary of testing methods for the ASTM D 2898 test for accelerated weathering of FRTW for fire testing

ASTM D 2898 Testing Methods			
<u>Step</u>	<u>Description/Requirements</u>	<u>Limit Value</u>	<u>Note</u>
Method A Exposure Cycle	Twelve, 1 week cycles	96hrs wet, 72hrs dry	-
	Water Application	0.7in/hr at 35-60°F	Fine spray, No recirculation
	Drying	135-140°F, 25ft/min Wind	Temp measured 1in above specimen
	Cycle specimen locations	After each cycle	Same number cycles in each location
Method B Exposure Cycle	24hr exposure cycle	4hrs dry, 4hrs wet, 4hrs dry, 4hrs wet, 8hrs rest	Repeat for 1000hrs total
	Water Application	0.3±0.02gal/min-ft ² , < 90°F	No recirculation for 3cycles, then ≥ 5gal fresh water each cycle
	Drying	150±5°F, 25ft/min Wind	Temp measured 1in above specimen
	Ultraviolet Exposure	Continuous during drying	GE type H275 RUV or Osram Ultra- Vitalox bulbs
	Cycle specimen locations	After one or more cycles	Same number cycles in each location
Conditioning	Equilibrate Moisture Content	Per applicable fire test	ASTM E 84, E 108, E286

After conditioning, a flame spread test is conducted to determine if an increase in classification is warranted. If the sample does not exhibit significant progressive combustion after a 20-minute period, FSI is at or below 25, and flames do not spread 10.5 feet beyond the centerline of the burners at any time, the sample has passes and can still be classified as FRTW.

International Building Code and NFPA 5000

The *International Building Code* (IBC) and *NFPA 5000* address the issue of FRTW in essentially the same way. Each uses the guidelines set out by ASTM D5644 for required chemical retention and references ASTM E84 for flame spread. The same requirement for flame spread index (FSI) of less than or equal to 25 must be maintained for both codes. Additionally, significant combustion cannot be observed for 20 minutes, and the flame front can never extend more than 10.5 feet past the centerline of the burners for the entire 30 minute of the standard test.

Both of these codes describe how all FR treated materials must be labeled showing the mark of an approving agency, the identification of the treating manufacturer,

the name of the treatment, the species of wood, FSI and smoke development index (SDI), method of re-drying, its conformance to ASTM E84 and other appropriate standards, and must include the words “No increase in the listed classification when subjected to the Standard Rain Test” if it is listed for use in exposed atmospheres (ASTM D2898).

Adjustments for design values shall be based on approved methods of investigation (any applicable ASTM test) where effects of temperature and humidity of in-service conditions are anticipated. Each manufacturer shall publish modification factors for service at ambient temperatures of up to 100°F for lumber used in roof framing and also must publish allowable maximum loads and spans for roof sheathing.

If FRTW is exposed to weather, it shall be identified as “exterior” to indicate no increase in FSI when subjected to ASTM D2898.

Moisture content of interior FTRW shall not exceed 28% when tested in accordance to ASTM 3201, at 92% RH. Exterior FRTW MC shall not exceed 19% for lumber and 15% for structural panels. Kiln dried specimens shall be dried at temperatures not exceeding those used in the applicable testing procedures. (International Code Council 2002) (National Fire Protection Association 2005)

It is clear that code officials for the *IBC* and *NFPA 5000* have seen significant worth in the standard testing procedures and the characteristics of FRTW that they asses.

NFPA 703

NFPA 703 is the standard for FRTW and fire retardant (FR) coatings for building materials. By definition in NFPA 703, FRTW is a wood product impregnated with chemical by a pressure process or other means during manufacture, which is tested in accordance with NFPA 255, ASTM E 84, or UL 723, has a listed flame spread index of

25 or less, and shown no evidence of significant progressive combustion when the test is continued for an additional 20-minute period; nor does the flame front progress more than 10.5 feet beyond the centerline of the burners at any time during the test (NFPA 2005).

For interior applications, NFPA 703 mandates that FRTW shall not have greater than 28%MC when tested in accordance with ASTM D 3201 at 92%RH, and lumber shall also be tested in accordance with ASTM D 5664.

For each species tested with ASTM D 5664, NFPA 703 states that design modification factors shall be developed via ASTM D 6841 and published by each manufacturer for service temperatures up to 100°F and for service roof framing which take into account climatological location.

For exterior applications, NFPA 703 states that all FRTW lumber products have 19%MC or less. It also states that if the lumber is air dried after treatment it must be protected from the weather, and if it is kiln dried, the drying temperature must not exceed the temperatures used in drying when being tested with ASTM D 5664.

Per NFPA 703, all FRTW products must be labeled in the same manner described in both the *IBC 2003* and *NFPA 5000*, discussed in the previous section. (NFPA 2005)

As in the *IBC 2003* and *NFPA 5000*, the steps that NFPA 703 mandates make it clear that the code officials believe strongly that the issues with FRTW addressed by the ASTM standard test methods are quite important.

2.4 Commercial FRTW

As described in Section 2.2 Overview of FRTW, in the past fire retardant treatments have depended upon phosphorus based compounds to achieve fire

performance properties. These compounds were known to have serious negative effects on strength and durability. Advancements in chemical research have brought about a new generation of FRTW formulations that contain no phosphates, but still exhibit exceptional fire performance properties without compromising critical engineering properties. (*FirePRO™*... 2001)

Many different FRTW commercial products have been specially formulated to target a specific quality in order to enhance their performance for specific tasks. For example, FRTW specified to be used in outdoor applications has enhanced corrosion resistance and hygroscopicity while the indoor version has superior structural capabilities. Because each product is designed to be used for a particular application, each has its own stipulations for design and installation practices. These procedures are listed in their respective product specification sheets which are located in Appendix A.1 Product Specifications for Various Commercial FRTW Products.

2.5 Truss Design

This section will provide an overview of the design approach used to establish truss member sizes for the thermal analysis and time to failure analysis to be discussed later.

Structural Analysis

A model living room was developed to obtain a truss design for thermal analysis. A square room, 16 feet by 16 feet, was used for the preliminary design, with truss joist spacing of 24 inches center to center. The live load used was 40 pound per square foot which was taken from the IBC 2003 edition, Table 1607.1 for a residential living room. The material used was Number 1 Southern Pine. Strength properties for the wood were

taken from Table 4B of the National Design Specification (NDS) Supplement, 2001 Edition. Load and Resistance Factor Design (LRFD) was the design method used for determining the overall loading while Allowable Stress Design (ASD) was used to size the actual members using the equations provided by the NDS. Hand calculations for the truss loading are shown in Appendix A.2 Typical Residential Floor Truss Loading while the computer program “TRUSS-4” was used to obtain each specific member force.

TRUSS-4

The computer program TRUSS was developed by John F. Fleming at the University of Pittsburg in 1988 for the stiffness analysis of plane trusses. Dr. Paramasivam Jayachandran revised the program in 1993 at Worcester Polytechnic Institute and renamed it TRUSS-4, which was the version used for this project.

TRUSS-4 uses Castigliano’s Second Theorem in the form of a series of matrices to evaluate highly indeterminate structures. Table 10 is a summary of the values necessary to run the program and those that are returned. Examples of full input and output files are shown in Appendix A.3 Sample Input and Output Files.

Table 10: Summary of input and output variables involved in using TRUSS-4

TRUSS-4 Input and Output			
Initial Input Values	Number of Joints	Output Values	Summary of Input
	Number of Members		
	Number of Materials		
	Number of Supports		
	Number of Loaded Joints		
Additional Inputs	Joint Locations	Output Values	Joint Displacements
	Material MOE		Member Axial Forces
	Member Locations and Cross-sectional Areas		Support Reactions
	Support Restraints		
	Joint Loads		

Designing an Economical Truss

Deciding on the truss configuration to be used began by comparing a simple original design to a truss that is used in a known fire rated configuration (*Southern... 2001-2006*). Both are shown in Figure 5 below as Type 1 and Type 2 respectively.

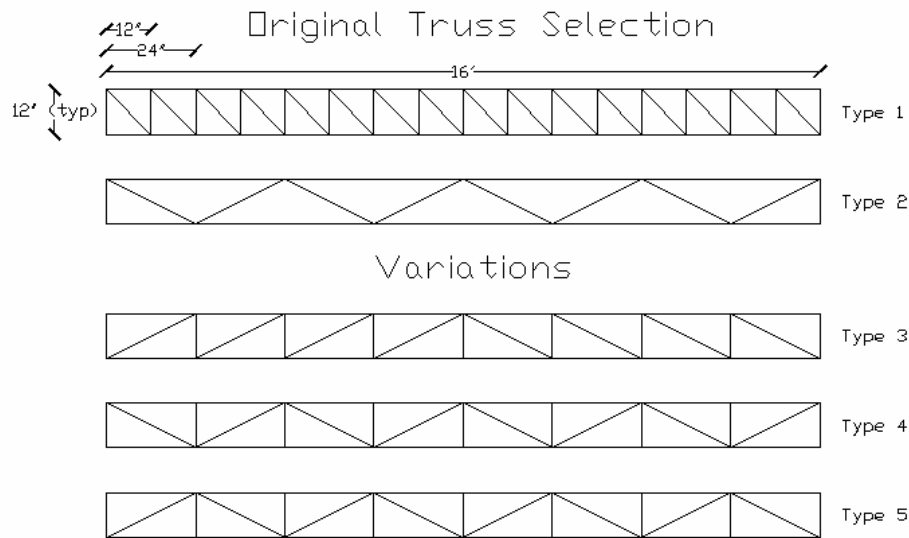


Figure 5: Original choices of truss configurations and the resulting variations

TRUSS-4 was then used to determine the axial loading each member would undergo using these particular arrangements. It was discovered that the compressive forces were significantly larger than the tensile forces, implying that the top chord would need to be much larger than the bottom. This gave way to the desire to design the most economical truss configuration for the floor system.

Because the focus of the redesign was to reduce the maximum compressive forces, each variation was designed using multiple diagonals slanting in towards the center of the truss because this will cause the members to be loaded compressively rather than in tension, allowing for a greater number of members to share the loading.

Criteria used for the final choice in order of importance was: smallest maximum compressive load, smallest maximum tensile load, the least number of redundant members (members with axial force of zero), and the least number of members. Truss Type 3 and 4 were chosen as the most economical truss configurations.

National Design Specification

The NDS provided a guide for the design of wood members using the ASD method. Basic equations for axially loaded members are shown below.

$$P' = F'_c \cdot A$$

$$F'_c = F_c \cdot C_D \cdot C_M \cdot C_t \cdot C_F \cdot C_i \cdot C_P \quad (7) \text{ (American Wood Council 2001)}$$

$$T' = F'_t \cdot A$$

$$F'_t = F_t \cdot C_D \cdot C_M \cdot C_t \cdot C_i \cdot C_F \quad (8) \text{ (American Wood Council 2001)}$$

Where P' and T' are the compressive and tensile capacities of a section with area A.

Other variables in Equations 1 and 2 are described in Table 11 below.

Table 11: Explanation of variables for ASD equations provided by the NDS

Equation (1)		Equation (2)	
F' _c	Adjusted compressive stress	F' _t	Adjusted tensile stress
F _c	Tabulated compressive stress	F _t	Tabulated tensile stress
C _D	Load duration factor	C _D	Load duration factor
C _M	Wet service factor	C _M	Wet service factor
C _t	Temperature factor	C _t	Temperature factor
C _F	Size factor	C _i	Incising factor
C _i	Incising factor	C _F	Size factor
C _P	Column stability factor		

2.6 Heat Transfer Models

This section will describe strength and weaknesses of two types of models that could be used for thermal analysis. Reasons for choosing the final model type are also discussed.

Finite Element Models

A finite element model (FEM) is beneficial because it uses complex numerical analysis methods that have the capability to solve very complicated problems by encompassing multiple modes of heat transfer all at once. But like all models, FEM has some important limitations that make it difficult to use in this type of analysis.

The most important limitation is something that is inherent to most if not all finite element models, and is the fact that there is no way to capture the chemical transformation from wood to char as the members heat up and eventually burn. This is a problem because char has a much lower thermal conductivity than that of wood, providing significant insulation after it is formed, therefore any analysis that excludes this phenomenon is not wholly representative.

One software package that uses FEM was investigated in this project but this limitation and other complications made it necessary to use a different type of model.

A model of a truss member with an attached plate was set up in a program called Thermal Analysis System (TAS). The downside to TAS was that it had difficulty representing the thermal relationship between the steel plate and the wood member. The wood acted as such a strong insulator that the model kept the steel temperature at whatever temperature the wood was directly underneath the plate. In reality the high thermal conductivity of steel would cause the plate to heat up much faster than the wood, regardless of the wood temperature.

Despite the many limitations of the program, it was intended to provide a measure of temperature versus time in the wood and steel to be compared to another model. Unfortunately further difficulty in getting time and temperature dependent variables to work with the transient analysis package led to its eventual abandonment.

Though an FEM analysis was not completed in this project, there are similar type studies that have been performed. The closest to this scenario would be a Ph.D. dissertation completed by Barry Wayne Gammon at the University of California, Berkeley in 1987 entitled “Reliability Analysis of Wood-Frame Wall Assemblies Exposed to Fire”.

Finite Difference Models

A finite difference model (FDM) is a thermal analysis method that uses specific time step intervals to calculate changes in temperature of a particular material over that interval. By adding the change in temperature to the initial temperature, the final temperature after the specified time is determined. This final temperature can then be used as the initial temperature to run the analysis again, and so on and so forth for as long as the user likes. This type of model works well when used in conjunction with a spreadsheet tool, but becomes tedious to set up for complicated problems using multiple materials and multiple modes of heat transfer.

Equation (9) below is the final form of the equation derived to determine the change in wood temperature as a function of time at a certain location in the cross-section.

$$\Delta T_w = \left[\frac{(T_g - T) \cdot \Delta t}{\frac{t_i}{k_i} + \frac{t_w}{k_w} + \frac{t_{ch}}{k_{ch}}} - (c_{pch} \cdot \rho_{ch} \cdot t_{ch} \cdot \Delta T_{ch}) - (c_{pi} \cdot \rho_i \cdot t_i \cdot \Delta T_g) \right] \cdot \left[\frac{1}{(c_{pw} \cdot \rho_w \cdot t_w) + 0.5(c_{pi} \cdot \rho_i \cdot t_i)} \right] \quad (9)$$

All input variables are described in

Table 12 below.

Finite Difference Equation Input Variables			
<u>Symbol</u>	<u>Description</u>	<u>Symbol</u>	<u>Description</u>
ΔT_w	Change in Wood Temperature	ρ_w	Wood Density
ΔT_g	Change in Gas Temperature	ρ_{ch}	Char Density
ΔT_{ch}	Change in Char Temperature	ρ_i	Insulation Density
ΔT_i	Change in Insulation Temperature	k_w	Wood Thermal Conductivity
T	Temperature at Increment Depth	k_{ch}	Char Thermal Conductivity
T_g	Gas Temperature	k_i	Insulation Thermal Conductivity
Δt	Change in Time	c_{pw}	Wood Specific Heat
t_w	Wood Thickness	c_{pch}	Char Specific Heat
t_{ch}	Char Thickness	c_{pi}	Insulation Specific Heat
t_i	Insulation Thickness	A	Area Being Heated

Table 12: Description of input variables for the finite difference equation for thermal analysis

This equation was developed using the basic principles of conservation of work and energy for heat transfer. It is a one dimensional model that enabled the determination of temperature variation through a wooden cross-section and via some assumptions, the depth of the char layer at any given time.

3.0 Methodology for Analysis

This chapter will provide an overview of the member sizes and characteristics of the truss plates used in the time and temperature dependent analysis of overall structural integrity. Several modes of failure have been established as well as criteria to determine the point of failure.

3.1 Evaluation of the Chosen Scenario

Truss Members

The design of typical truss members was completed to decide the member cross-sectional areas should for use during the thermal analysis portion of the project. Heat will be introduced to the truss as the fire in the room below heats the gypsum board layer, and is conducted into the bottom chord. The thermal analysis is simplified by assuming that conduction is the primary form of heat transfer in this situation, and that there are no radiative effects from the heated gypsum layer to the exposed sides of the members. Since the bottom chord of the truss is the only member contact with the gypsum board protection, its dimensions were used in thermal analysis. Member sizes for the bottom chords of the various trusses are summarized in Table 13 below.

Table 13: Bottom chord member sizes for Type 3 and 4 trusses using sawn lumber and FRTW

Sawn Lumber				FRTW			
Truss Type	Span	Chord Size: Nominal (Actual)	Area (in ²)	Truss Type	Span	Chord Size: Nominal (Actual)	Area (in ²)
3	16'	1"x4" (0.75"x3.5")	2.625	3	16'	2"x4" (1.5"x3.5")	5.25
	20'	1"x6" (0.75"x5.5")	4.125		20'	2"x6" (1.5"x5.5")	8.25
	24'	2"x6" (1.5"x5.5")	8.25		24'	2"x6" (1.5"x5.5")	8.25
4	16'	2"x4" (1.5"x3.5")	5.25	4	16'	Double 2"x4" (3.0"x7.0")	21.0
	20'	2"x6" (1.5"x5.5")	8.25		20'	2"x6" (1.5"x5.5")	8.25
	24'	2"x6" (1.5"x5.5")	8.25		24'	Double 2"x6" (3.0"x11.0")	33.0

Each FRTW member was designed as ordinary sawn lumber using the NDS except the final allowable design value was multiplied by the factor for tensile strength listed in

Table 14 in Section 3.2 Strength Modeling for an estimated maximum 100°F service temperature.

Truss Plates

Because this project is focusing on the tension chord of the truss, a parallel oriented truss plate is examined. A parallel plate is aligned so that its longest dimension is parallel to length of the member, or parallel to the wood grain. The type of truss plate examined was chosen to be the same as one of those examined by White, et al, in their experiments. Their parallel plate was made of Grade A, 20 gauge steel, with 1/3 inch long teeth at a density of 9.4 teeth per square inch. The dimensions of the plate were 3 inches by 7.5 inches long.

Fire Scenario and Thermal Analysis

Because the strength models described in Section 3.2 Strength Modeling are based upon experiments using the ASTM E-119 standard exposure, the same time/temperature curve was also in the FDM to evaluate wood temperature. Temperature values were taken at 100 second increments from the standard fire curve for ASTM E-119 and input as the gas temperature for the FDM.

Insulation thicknesses of 1/2" and double thick 5/8" (1.25 inches) were evaluated with standard gypsum board as the insulating material.

Wood temperature as a function of time was determined at 1/2" increments up to 5.5 inches, which is the widest cross-sectional dimension of the largest bottom chord member determined by the truss design (nominal 2x6).

To account for char formation, the wood thickness at any point was equal to the increment depth minus the char thickness. Char thickness was defined as the depth

where a temperature of 288°C has reached, which is the approximate temperature that wood must reach in order to begin char formation. This depth was determined via linear interpolation between the temperatures at the surface of the wood and at the increment being evaluated. Because there is interdependency between temperature and char depth, a spreadsheet was used to iterate between this and several other variables that shared dependency with temperature (density, thermal conductivity, specific heat), until there was a closure of 0.001.

Thermal properties of wood are known to change with temperature. Figure 6 shows how density, thermal conductivity and specific heat vary as temperature increases. To capture this phenomenon, each curve was broken down into its linear parts, and simple slope-intercept equations written for each of them. Each layer could be assigned its own thermal properties depending on their respective temperatures. Char was assigned thermal properties corresponding to the portions of the graph after the 288°C mark.

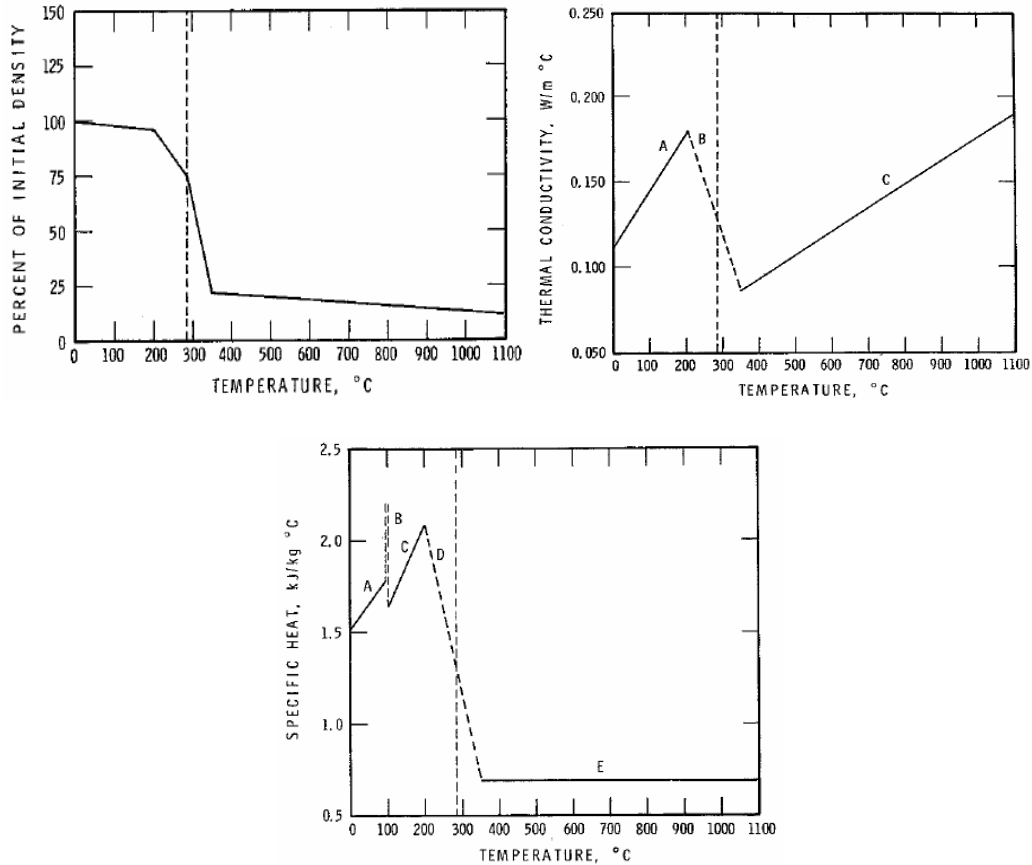


Figure 6: Thermal properties of wood as a function of temperature (Lie 1992)

3.2 Strength Modeling

Thermal Degradation of Wood

Empirical equations for the thermal degradation of the sawn lumber strength properties were determined by White et al. and are described in the following equations.

$$\frac{P_t}{P_o} = \frac{T_o \cdot t_e}{(T_o \cdot t_e) + (\gamma_P \cdot A_t)} \quad (10)$$

$$\gamma_P = \frac{T_c^{0.5}}{100} (\text{MOE}); \frac{T_c}{198} (\text{Tension / Compression}); \left(\frac{T_c}{215}\right)^6 (\text{Bending}) \quad (11)$$

$$A_t = T - T_o; T = \frac{T_s + 2T_c}{3} \quad (12)$$

Where t_e is the exposure time in minutes, T_o is the initial room temperature, T_c is the center temperature of the lumber at time t_e , T_s is the surface temperature of the lumber at time t_e , A_t is the normalized change in wood temperature and is defined in Equation 6, P_t is any strength property, P_o is the property being evaluated at room temperature, and γ_p is a correction factor for each strength property.

Equations (10), (11), and (12) are based upon an idealized plenum time/temperature exposure equal to that of the ASTM E-119 standard exposure. The equation for A_t is derived from trapezoidal rule when using the approximation that the temperature boundary layer in the wood is parabolic in nature. This research was structured to exclude the effects of charring in order to define thermal degradation of wood sections before char forms; therefore there is no reduction in cross-section.

Equations for the thermal degradation of FRTW properties at temperatures seen in a fire scenario have not yet been developed, making this a topic for further research. However, the trend can be approximated by inspection of the reduction factors for the commercially available FRTW which are tabulated below. Typically factors will decrease as temperature increases though there are some outliers since these values are taken from specifications for different brand products.

Temp. °F	FRTW Design Factor (Southern Pine)			
	Tension	Comp.	MOE	Bending
80	0.92	0.94	0.98	0.89
80	0.77	0.93	0.88	0.85
100	0.88	0.94	0.95	0.91
150	0.85	0.67	0.91	0.8
150	0.65	0.85	0.89	0.79
180	0.82	1	0.95	0.84

Table 14: Design factors for FRTW for service up to the given temperature

Figure 7 below illustrates a trend that was created for the tensile capacity using the design values in Table 14. Graphs and trends for the remaining strength properties can be

viewed in Appendix A.4 Strength Properties of FRTW vs. Temperature. Values listed for 180°F created outliers in all categories, so they were eliminated in order to achieve a more representative trendline. Linear, logarithmic, power, and exponential trendline functions were each evaluated and best fit was chosen based upon regression values that are shown in each figure.

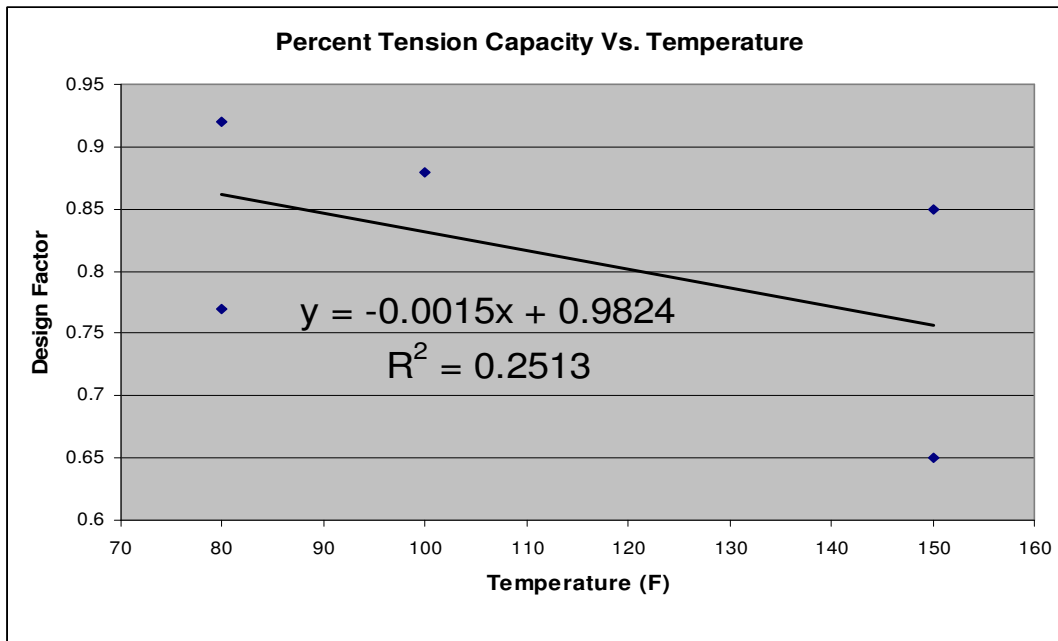


Figure 7: Tensile capacity of FRTW versus temperature in terms of manufacturer published design factors

Thermal Degradation of Steel

Thermal degradation models for steel have been developed and are published by the Society of Fire Protection Engineers (SFPE). Equations (13) (SFPE 2002) and (14) are used to determine the MOE of a steel section at any temperature T, and Equations (15) (SFPE 2002), and (16) (SFPE 2002) are used to determine the yield stress of steel at any temperature T.

$$MOE_{\theta} = \left(1 + \frac{T}{2000 \cdot \ln\left(\frac{T}{1100}\right)} \right) \cdot MOE_o \quad (13) \text{ (SFPE 2002)}$$

$$0 < T \leq 600^{\circ} C$$

$$MOE_{\theta} = \left(\frac{690 - 0.69T}{T - 53.5} \right) \cdot MOE_o \quad (14) \text{ (SFPE 2002)}$$

$$T > 600^{\circ} C$$

$$\sigma_{y\theta} = \left(1 + \frac{T}{900 \cdot \ln\left(\frac{T}{1750}\right)} \right) \cdot \sigma_{yo} \quad (15) \text{ (SFPE 2002)}$$

$$0 < T \leq 600^{\circ} C$$

$$\sigma_{y\theta} = \left(\frac{340 - 0.34T}{T - 240} \right) \cdot \sigma_{yo} \quad (16) \text{ (SFPE 2002)}$$

$$T > 600^{\circ} C$$

As described in the following section, an average maximum deflection limit of 30° was used to categorize tooth failure, defined by inspecting photographs from previous work concerned with peeling failures (Percival, et al 1971). Equation (17), for the maximum deflection of a uniformly loaded cantilever beam, was used to determine maximum deflection along the tooth.

$$\delta_{MAX} = \frac{\omega \cdot L^4}{8EI} \quad (17)$$

Equation (17) is dependent upon MOE; therefore it was in this manner that thermal effects were incorporated into the evaluation of plate failure. Initial plate material properties for this analysis were taken from product specifications on hot-dipped galvanized steel, provided by the AK Steel Corporation and obtained via their website (AK Steel Corp. 2000).

The plate itself was modeled to fail in tension. By using the simple equation for tensile capacity, shown below as Equation (18), thermal effects could be incorporated using the degradation equations for yield stress provided by the SFPE.

$$F_T = \sigma_y \cdot A_s \quad (18)$$

3.3 Failure Modes and Criterion

Tooth Withdrawal

Tooth withdrawal will occur when the loading on the joint exceeds the total capacity of the involved connecting teeth. At elevated temperatures, wood begins char and excessive loading is transferred to the remaining load-carrying teeth if charring occurs across the tooth or to the tips of the teeth if charring occurs along the tooth. A combination of the wood being locally crushed under the tooth, and tooth deformation from loading, will create large tip deflections with less wood surface area for the steel tooth to grip. At some critical angle and temperature, degraded tooth bending strength, reduced contact of the wood, and increased localized loading will cause the teeth to peel out of the section

Because the model developed for this project addresses char in only one direction, tooth withdrawal via char formation will occur when the char layer passes enough rows of teeth so that the remaining teeth have insufficient capacity to carry the design load. Tooth withdrawal could also occur if increased temperature of the teeth causes bending strength to degrade to the point where the residual tooth capacity is below the required capacity. A combination of these two events is another possible scenario.

Tooth temperature is approximated as the temperature of the wood section at the same location. The critical average deflection point used to determine the time of failure

is one third of the tooth length, or about 30°. This value was established through the inspection of photographs taken after tension testing was done on sawn lumber and FRTW joints connected with metal truss plates. This research was conducted at the FPL and the report is published under the title “Technical Note No. 6” (Percival, Suddarth 1971).

Mechanical Failure

Mechanical failure was defined for the wood sections by determining the critical cross-sectional area needed to carry the design load. When the section has charred to the point where the critical area is larger than the residual area, the member has failed.

Failure of the steel plate was defined as when the tensile stress in the plate exceeds the maximum allowable tensile stress after thermal degradation.

4.0 Results and Discussion

This chapter summarizes the results obtained from the FDM for temperature variation through the wooded cross-section. With this data, the thermal degradation models have been evaluated and applied to each truss to determine subsequent failure times after exposure. Also, failure analysis results are summarized and their overall implications are discussed.

4.1 Model Analysis

Analysis using the FDM described in Section 2.6 Heat Transfer Models resulted in the data shown in Figure 9 and Figure 18 for 1/2" and double 5/8" thick gypsum board protection respectively.

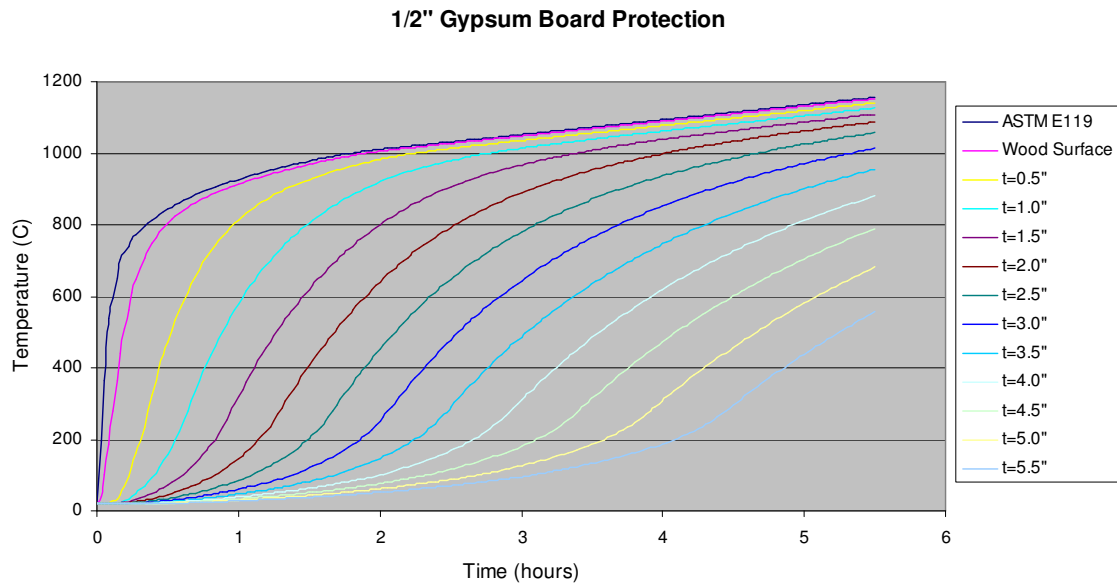


Figure 8: Temperature of wooden member at various depths when protected by 1/2" gypsum board and exposed to the ASTM E-119 fire curve

2x5/8" Gypsum Board Protection

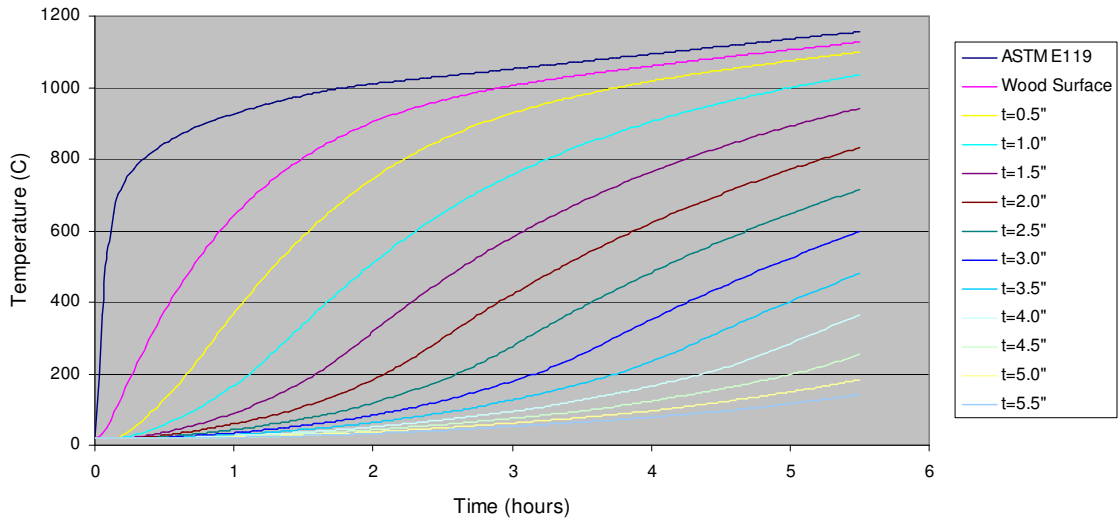


Figure 9: Temperature of wooden member at various depths when protected by double 5/8" gypsum board and exposed to the ASTM E-119 fire curve

It is shown by these figures that the wood temperature decreases as the depth increases, and by increasing the thickness of the insulation, thermal penetration was postponed significantly.

Using this data, the models described in Section 3.2 Strength Modeling for the thermal degradation of sawn lumber and the one developed for FRTW using published design values are evaluated as a function of time for residual tensile and compressive strength when protected by 1/2" and double 5/8" gypsum board insulation.

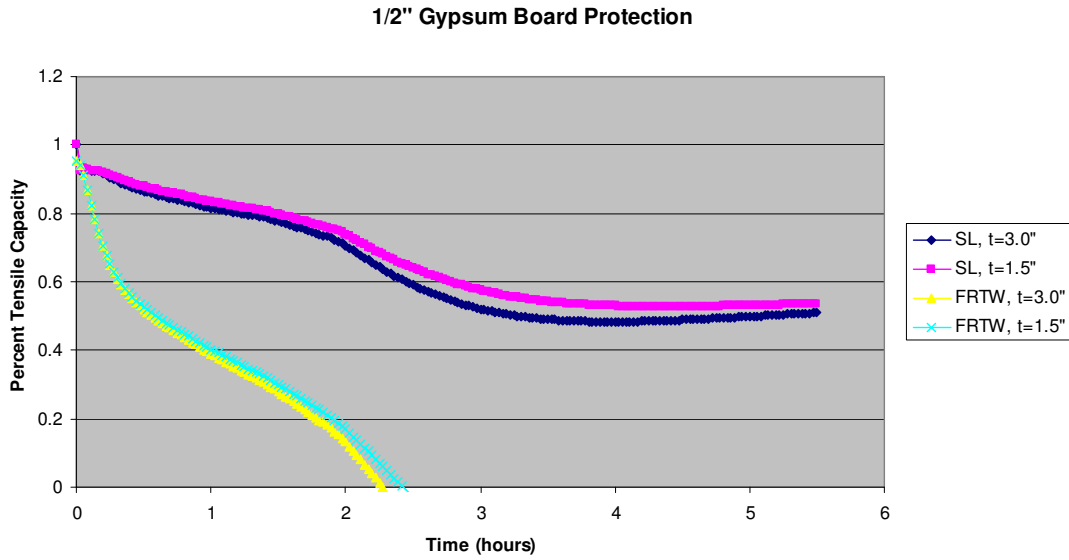


Figure 10: Residual tensile capacity of sawn lumber and FRTW when exposed to the ASTM E-119 fire curve and protected by 1/2" gypsum board

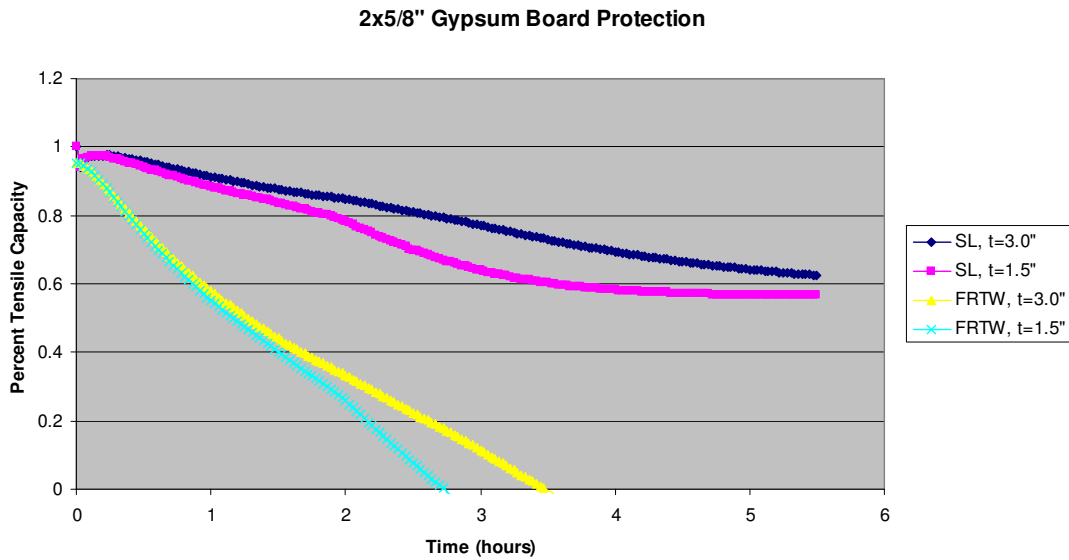


Figure 11: Residual tensile capacity of sawn lumber and FRTW when exposed to the ASTM E-119 fire curve and protected by double 5/8" gypsum board

Figure 10 and Figure 11 show that the residual tensile capacity of sawn lumber as compared to that of FRTW, when exposed to the ASTM E-119 fire curve and evaluated using the strength degradation correlations described earlier, is much more resilient.

These figures also show that as insulation thickness increases, so does the ability to maintain residual cross-sectional capacity for a longer period of time.

4.2 Failure Analysis

The first mode of failure that was investigated was that of a simple mechanical failure of the wood section without using degraded capacity. Table 16 below summarizes the results of this analysis. Highlighted members are those that correlate best with combined fire endurance ratings of structural components as listed in Table 15 below.

Table 15: Expected fire endurance times for specific construction components (ASCE SFPE 29 1999)

Expected Fire Ratings of Construction Materials	
Description of Building Element	Time
1/2" gypsum board	15min
5/8" gypsum board	20min
Wood truss floor assemblies, 24"c/c	5min

Table 16: Summary of failure times for each truss type and span for sawn lumber, FRTW, and different member orientations. Note the initial load to capacity ratios and the corresponding times to failure.

100% Residual Cross-Sectional Strength and ASTM E-119 Exposure							
Truss Type	Span(ft)	Material	Nominal Member Size	Member Orientation	1/2" Gypum Failure Time(min/sec)	2x5/8" Gypum Failure Time(min/sec)	Load to Capacity Ratio
3	16	Sawn Lumber	2 x 4	Horizontal	32 / 1900	68 / 4100	0.45
			2 x 4	Vertical	75 / 4500	142 / 8500	
		FRTW	Double 2x4	Horizontal	87 / 5200	162 / 9700	0.26
			Double 2x4	Vertical	105 / 6300	188 / 11300	
	20	Sawn Lumber	2 x 6	Horizontal	30 / 1800	67 / 4000	0.47
			2 x 6	Vertical	120 / 7200	213 / 12800	
		FRTW	2 x 6	Horizontal	27 / 1600	60 / 3600	0.54
			2 x 6	Vertical	102 / 6100	187 / 11200	
	24	Sawn Lumber	2 x 6	Horizontal	20 / 1200	48 / 2900	0.69
			2 x 6	Vertical	63 / 3800	128 / 7500	
		FRTW	2 x 6	Horizontal	15 / 900	38 / 2300	0.79
			2 x 6	Vertical	43 / 2600	92 / 5500	
4	16	Sawn Lumber	2 x 4	Horizontal	15 / 900	40 / 2400	0.78
			2 x 4	Vertical	30 / 1800	67 / 4000	
		FRTW	Double 2x4	Horizontal	63 / 3800	125 / 7500	0.44
			Double 2x4	Vertical	77 / 4600	145 / 8700	
	20	Sawn Lumber	2 x 6	Horizontal	23 / 1400	55 / 3300	0.60
			2 x 6	Vertical	85 / 5100	160 / 9600	
		FRTW	2 x 6	Horizontal	22 / 1300	48 / 2900	0.68
			2 x 6	Vertical	67 / 4000	128 / 7700	
	24	Sawn Lumber	2 x 6	Horizontal	8 / 500	25 / 1500	0.97
			2 x 6	Vertical	10 / 600	30 / 1800	
		FRTW	Double 2x6	Horizontal	52 / 3100	103 / 6200	0.55
			Double 2x6	Vertical	100 / 6000	182 / 10900	

One important finding that can be seen from this table is that member orientation had a large impact on time to failure. Horizontal orientation denoted that the beam was analyzed as if its long dimension was in contact with the gypsum board, and vertical orientation denoted that the short dimension was in contact with the insulation. Because the FDM was set up as a one dimensional model that neglected radiation effects, char could only form starting at the gypsum layer and proceeding towards the back face of the member. Subsequently, if the long dimension chars only a slight amount, the resulting area loss is much greater than if char forms on the short dimension, making the time to reach the critical area far less when analyzing horizontal members than vertical members.

Another important finding can be noticed by inspection of the initial load to capacity ratios (ILCR). This is a measure of how much of the beams cross-section is undergoing loading in-service. If the ILCR is close to 1.0, almost all the area is needed to carry the design load. This will happen if the member capacity was just large enough and the next size up was not needed. If the ILCR is far less than one, much of the cross-section is not needed. This often happens if one member capacity is slightly too low and the next larger size must be chosen though only a small amount of the added capacity is actually needed. Table 16 shows how when the ILCR is close to one, and only a small amount of area needs to be lost in order to reach the critical level, the truss will fail rather quickly. When the ILCR is between 0.5 and 0.8, the truss failure time is longer and, for the horizontal orientation, is on the same order as that predicted by Table 15.

Only trusses that exhibited failure times most closely resembling what was predicted by ASCE SFPE 29 99 (highlighted in Table 16) were used for further analysis. The next step was to incorporate strength loss of the residual cross-section of each

member due to thermal exposure. Strength reduction factors were taken from the data shown in either Figure 10 or Figure 11, corresponding to the insulation thickness being evaluated. Reduction factors and the subsequent reduced failure times are shown in Table 17 below.

Table 17: Summary of failure times for selected trusses when using strength reduction models for the residual cross-sections

Updated Failure Times of Best Fit Members Using Degraded Residual Cross-Section								
Truss Type	Span(ft)	Material	Nominal Member Size	Member Orientation	% Residual Capacity (1/2" gypsum)	% Residual Capacity (2x5/8" gypsum)	1/2" Gypsum Failure Time(min/sec)	2x5/8" Gypsum Failure Time(min/sec)
3	16	Sawn Lumber	2 x 4	Horizontal	0.875	0.87	27 / 1600	62 / 3700
	20	Sawn Lumber	2 x 6	Horizontal	0.878	0.873	27 / 1600	60 / 3600
		FRTW	2 x 6	Horizontal	0.545	0.552	8 / 500	25 / 1500
	24	Sawn Lumber	2 x 6	Horizontal	0.899	0.905	17 / 1000	40 / 2400
		FRTW	2 x 6	Horizontal	0.652	0.688	15 / 900	37 / 2200
4	16	Sawn Lumber	2 x 4	Horizontal	0.912	0.921	10 / 600	33 / 2000
	20	Sawn Lumber	2 x 6	Horizontal	0.891	0.892	22 / 1300	50 / 3000
		FRTW	2 x 6	Horizontal	0.58	0.622	20 / 1200	50 / 3000
	24	Sawn Lumber	2 x 6	Horizontal	0.965	0.965	7 / 400	12 / 700

An important finding from this analysis is seen when inspecting failure times for FRTW. Because, according to the model that was developed, FRTW strength decreases severely with temperature, time to failure for the FRTW trusses were also dramatically reduced. This is evident by comparing the failure time for the highlighted truss in Table 17 and comparing it to its corresponding failure time in Table 16. For the ½” gypsum board protection, the failure time was reduced by a factor of about 3.5 and a factor of about 2 for the double 5/8” gypsum. Because this isn’t representative of the nature of FRTW, which is expected to perform better in fire, the model for strength reduction must come into question. This model was derived from published design values for FRTW when tested in accordance to ASTM D 5664. This test uses the highest temperatures that could be expected in-service, which are relatively low temperatures from the standpoint of a fire scenario, and exposes the specimens for long periods. As was described in

Section 2.2 Overview of FRTW, this is the exact scenario that causes the materials to degrade and fail when used in construction, but is likely not the representative of how FRTW will degrade in extreme temperatures for much shorter durations.

The next analysis for this project was completed by incorporating connector tooth deflection failure. Charring, residual wood cross-section strength loss, thermal degradation of steel, and average tooth deflection limits were all analyzed simultaneously to determine the ultimate failure time. Table 18 below shows the new calculated times to failure and compares them to the results shown in Table 17.

Table 18: Summary of failure times and failure modes for the selected trusses when considering tooth deflection failures and comparison to failure times when only considering thermal degradation of wood

Failure Time: Best Fit Members, Degraded Residual Cross-Section, Connection Failure											
Truss Type	Span (ft)	Material	Nominal Member Size	1/2" Gypsum Wood Only (min/sec)	1/2" Gypsum Connection (min/sec)	Failure Initiating Mode	2x5/8" Gypsum Wood Only (min/sec)	2x5/8" Gypsum Connection (min/sec)	Failure Initiating Mode	Plate Load to Capacity Ratio	Member Load to Capacity Ratio
3	16	Sawn Lumber	2 x 4	27 / 1600	27 / 1600	Wood Failure	62 / 3700	62 / 3700	Wood Failure	0.44	0.45
	20	Sawn Lumber	2 x 6	27 / 1600	17 / 1000	*Char Depth	60 / 3600	42 / 2500	*Char Depth	0.68	0.47
		FRTW	2 x 6	8 / 500	8 / 500	Wood Failure	25 / 1500	25 / 1500	Wood Failure	0.68	0.54
	24	Sawn Lumber	2 x 6	17 / 1000	2 / 100	Tooth Deflection	40 / 2400	5 / 300	Tooth Deflection	0.99	0.69
		FRTW	2 x 6	15 / 900	2 / 100	Tooth Deflection	37 / 2200	5 / 300	Tooth Deflection	0.99	0.79
4	16	Sawn Lumber	2 x 4	10 / 600	10 / 600	Wood Failure	33 / 2000	33 / 2000	Wood Failure	0.74	0.78
	20	Sawn Lumber	2 x 6	22 / 1300	17 / 1000	*Char Depth	50 / 3000	42 / 2500	*Char Depth	0.86	0.60
		FRTW	2 x 6	20 / 1200	17 / 1000	*Char Depth	50 / 3000	42 / 2500	*Char Depth	0.86	0.68
	24	Sawn Lumber	2 x 6	7 / 400	Immediate	Tooth Deflection	12 / 700	Immediate	Tooth Deflection	1.38	0.97

*Char formation led to insufficient tooth capacity

Some results now match well with the expected endurance times described in Table 15. Important patterns were seen when inspecting the initiating failure modes and corresponding failure times. When char depth, leading to insufficient tooth capacity, was the failure mode, threshold times for the 1/2" gypsum and double 5/8" gypsum scenarios

were established at around 17 minutes and 42 minutes respectively. This occurred because when the char layer reached the first row of teeth, the remaining teeth involved were insufficient in number and/or strength capacity to withstand their loading. This failure was prevalent when the member ILCR was low enough so that the remaining cross-section was sufficient up to the point where the charring passes the first row of teeth, causing failure. Conversely, when failure times were found to be below the threshold limit, member ILRC was closer to 1.0 and failure times did not change. This occurred because the section loss from charring would cause member failure before the char front could reach the first row of teeth.

Tooth deflection failures, highlighted in Table 18, occurred when the plate ILCR was higher than around 0.9. The 30% deflection limit was reached very prematurely in these cases because the plate used was either barely sufficient to carry the load or insufficient from the start. This can be attributed to the fact that the plate sizes were assumed from the start, and furthermore all assumed to be the same, without consideration of loading. One interesting relationship that was noticed in this scenario was that when the plate ILCR was about 15% greater than the member ILCR, but not greater than 0.9, char depth would be the failure. As soon as the plate ILCR became less than 15% greater than the member ILCR, the wood section would fail first.

Plate rupture failure mode was the final mode to be analyzed. Because there was a lack of temperature versus time information for the plate portion of the connections, the plate temperature was taken to be the average of the tooth temperatures. Table 19 below shows the time to failure results when considering the possibility of every type of failure investigated by this thesis.

Table 19: Summary of failure times when considering all modes of failure

Failure Time: Best Fit, Thermal Degrade, Connection, Plate Failure											
Truss Type	Span (ft)	Material	Nominal Member Size	1/2" Gypsum Connection (min/sec)	1/2" Gypsum Plate (min/sec)	Failure Initiating Mode	2x5/8" Gypsum Connection (min/sec)	2x5/8" Gypsum Plate (min/sec)	Failure Initiating Mode	Plate Load to Capacity Ratio	Member Load to Capacity Ratio
3	16	Sawn Lumber	2 x 4	27 / 1600	27 / 1600	Wood Failure	42 / 2500	42 / 2500	*Char Depth	0.44	0.45
	20	Sawn Lumber	2 x 6	17 / 1000	17 / 1000	*Char Depth	42 / 2500	42 / 2500	*Char Depth	0.68	0.47
		FRTW	2 x 6	8 / 500	8 / 500	Wood Failure	25 / 1500	25 / 1500	Wood Failure	0.68	0.54
	24	Sawn Lumber	2 x 6	2 / 100	2 / 100	Tooth Deflection	5 / 300	5 / 300	Tooth Deflection	0.99	0.69
		FRTW	2 x 6	2 / 100	2 / 100	Tooth Deflection	5 / 300	5 / 300	Tooth Deflection	0.99	0.79
4	16	Sawn Lumber	2 x 4	10 / 600	10 / 600	Wood Failure	33 / 2000	33 / 2000	Wood Failure	0.74	0.78
	20	Sawn Lumber	2 x 6	17 / 1000	17 / 1000	*Char Depth	42 / 2500	42 / 2500	*Char Depth	0.86	0.60
		FRTW	2 x 6	17 / 1000	17 / 1000	*Char Depth	42 / 2500	42 / 2500	*Char Depth	0.86	0.68
	24	Sawn Lumber	2 x 6	7 / 400	Immediate	Connection	12 / 700	Immediate	Connection	1.38	0.97

It can be seen that when incorporating the plate failure as well, there is essentially no impact on the failure times. This shows that when using the 30% deflection failure criteria for the connector plate teeth, tooth deflection is a more critical limit than plate tensile capacity. Because the truss plate was extremely under-designed for the 24 foot, sawn lumber, Type 4 truss, the true mode of failure cannot be readily determined.

In this scenario, whether the tooth failed by deflection limit or via char depth, it was ultimately the amount of teeth involved in carrying the load that was the limiting factor. This, combined with the other data, suggests that when member ILCR is low enough, and the number of rows of teeth involved is large enough, both the wood and tooth capacities would be sufficiently large to withstand charring and thermal degradation so that the plate itself will have ample time to heat, thermally degrade, and eventually fail in tension.

Though these results can show a structural engineer many things about the nature of light-weight truss failure modes, they are limited in their ability to capture how FRTW would behave as a substitute for normal sawn lumber. To further the capabilities of this type of analysis, future testing is needed.

5.0 Experimental Design

It is evident that there is a great need for further research in the area of FRTW before a more representative analysis can be completed. The purpose of this chapter is to provide experimental procedures that will facilitate the gathering of necessary information that is essential for advancing the work that has been described herein. Experiments to test load capacity as a function of time and temperature target tension members specifically because it is assumed that the bottom chord of a truss will be the first member significantly affected by fire and will be the controlling factor at failure.

Due to the inherent variability that occurs when using a material such as wood, it is suggested that each separate species be tested separately, as is done with other standard test methods using wood. Furthermore, if testing is to be done to characterize particular shipment or other quantity of wood, specimens should be chosen to be the most representative of the lot, as is mandated by other standard tests using wood.

5.1 FRTW Thermophysical Properties

Thermophysical properties are essential in any type of thermal analysis. The development of accurate values for these properties, especially as a function of temperature, would greatly advance the work completed in this thesis. Once these values have been determined, the same FDM model that was developed could be used for thermal analysis of FRTW, and a more genuine representation of its comparison to sawn lumber can be made.

These proposed testing methods are for the determination of thermal conductivity, specific heat capacity, and density, as a function of temperature, for FRTW. The ASTM standard test procedures for determining conductivity and specific heat have several

bounding limits that are not wholly satisfied in this case. Because thermal analysis relies heavily on these types of parameters, their accuracy is quite important; therefore due to their possible inapplicability and overall complexity, these tests are only summarized briefly. Possible alternative tests are also described. Some past work has been done to determine the thermo-physical properties of untreated lumber as a function of temperature (Knudson, Schniewind 1975), but the procedures used for their experiments could not be located for comparison to the suggested methods.

Thermal Conductivity

ASTM E 1225 is the standard test method for determining thermal conductivity of solids by means of the guarded-comparative-longitudinal heat flow technique. This test is intended to be used for materials with conductivities in the range of 0.2 to 200W/m-°K over a range of 90 to 1300°K, but it is stated that it can be used for materials outside of this range with decreased accuracy. Wood has thermal conductivity on the order of 0.1-0.2W/m-°K in this range. This test is intended to be used for homogeneous materials, where wood is not, but is the most applicable standard at ASTM for testing this property.

To begin, a specimen of the material to be tested is placed under load, applied by a clamp, between two equal-size reference specimens with known thermal properties. Load is applied to the stack to ensure good contact between specimens. A thermal guard cylinder, used to minimize heat losses, is placed around the test stack and contains at least one heater to control its temperature profile. The guard must have approximately the same temperature gradient as the test stack because if the gradient is largely different, there will be heat transfer in one direction or the other, leading to skewed results. Figure 12 below shows schematics of an example testing arrangement.

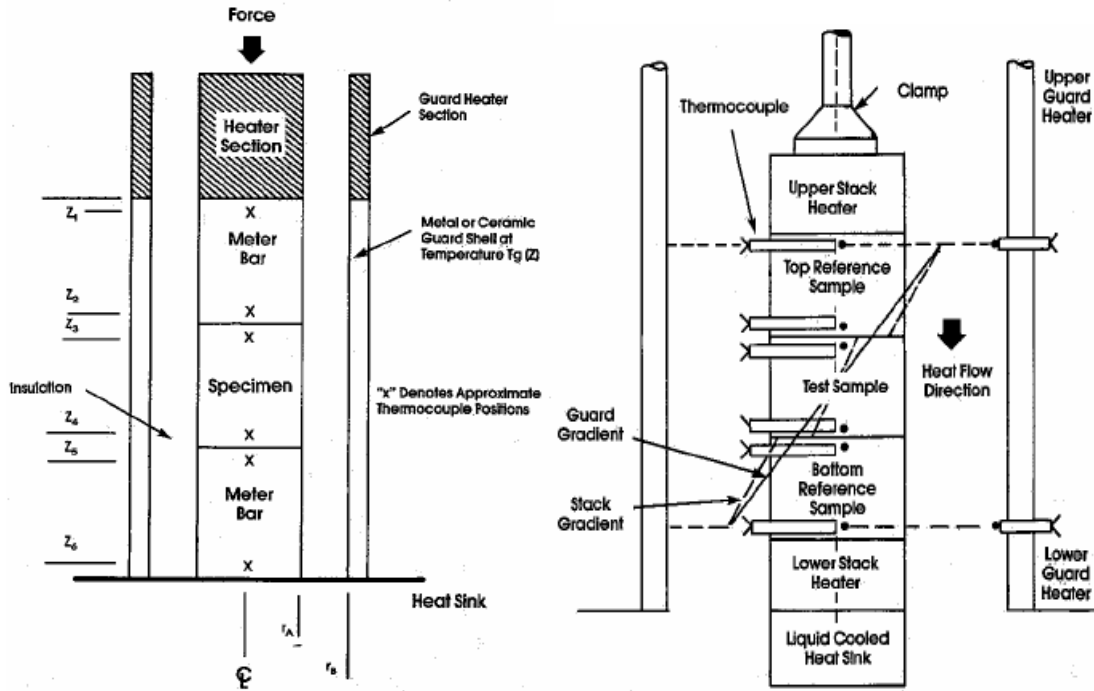


Figure 12: Schematics of test configuration and instrumentation for ASTM E 1225 (ASTM Int. 2004)
 For equilibrium conditions at any temperature, thermal conductivity of the unknown is

derived from the measured temperature gradients in the respective specimens and the thermal conductivity of the reference material using simple equations provided in the test procedures. (ASTM International, Vol. 14.02 2004)

Specific Heat Capacity

ASTM E 1269 is the standard test method for determining specific heat capacity by differential scanning calorimetry. The normal temperature range of this test is 100°C to 600°C, which is about half the temperatures usually associated with fire scenarios. This range can be extended, however, depending upon the use of special instrumentation and specimen holders.

This method, using a differential scanning calorimeter (DSC), will heat the test material at a controlled rate in a constantly nitrogen purged atmosphere. The difference in heat flow into the unknown specimen and a reference material, due to energy changes

in the materials, is continually recorded. Synthetic sapphire is always used as the reference material in this test and specific heat values are listed in a table in the test procedures for values up to 1000°K and as low as 150°K.

After the test chamber containing the unknown material is heated or cooled to the desired initial temperature at a rate of 20°C per minute, it is held at this temperature for an indefinite amount of time (no less than 4 minutes) for equilibration. In the case of wood products, the user should wait a considerable amount of time longer than the minimum value since wood is known to have low thermal diffusivity. Variations with this hold time can be implemented and differences in resulting values recorded to determine the optimum equilibration period. The test specimen is then heated at 20°C per minute to the desired final temperature continuously recording the thermal curve. With thermal curved for the synthetic sapphire, unknown material, and one from an empty specimen holder, simple equations given in the test procedures can be used to determine the specific heat capacity of the unknown material at the temperatures all along the thermal curve. (ASTM International, Vol. 14.02 2004)

Density

Density testing will begin by taking multiple formulations of FRTW and control specimens of normal sawn lumber, using the same species, equal dimensions, and approximately equal retention levels. Retention level of the pieces, using a particular agent, would not be below midpoint of the retention range as specified for the species by the certifying agency. Use sample dimensions of 10cm by 10cm by 2cm thick. Thinner samples will ensure that when heated, less hold time will be needed to ensure equal temperature levels throughout the specimen. FRTW is not allowed to be milled before

installation, so the specimens must be treated after being cut to size. Multiple species will also be tested in order to obtain a wide range of results for comparison.

Make sample sets of 25 specimens, with five samples of four types of FRTW and five samples of sawn lumber pieces. Create as many specimen sets for as many different temperatures are to be tested for the corresponding density. Equilibrate the specimens to 65%RH and 19%MC. Weigh the blocks to a sensitivity of ± 0.01 grams. Load one sample set into an oven with each piece oriented vertically to promote even, fast heating. Before testing begins, an optimal equilibration period for achieving even specimen temperature distribution should be established for each oven to ensure quality results. Heat the oven at a rate of 10°C per minute to the desired testing temperature and hold for the established optimal temperature equilibration period.

When hold time is completed, weigh blocks again to the same sensitivity as quickly as possible to maintain desired temperature. If oven safe weight measurement techniques are available, it would be best to weigh the specimens in the heated environment. The final weight divided by the initial volume is the density of the specimen. Density will be recorded as a percentage of the initial sample density for easy comparison between the control, different FRTW products, and eventually different species.

The maximum temperature used for testing intact wood specimens will be around 300°C because after this point charring will occur. Only intact specimens are eligible for measurement because char is essentially its own material to be tested for density separately. This can be done because on the plot of wood density versus temperature, the point where wood ends and char begins can be idealized as the same point. Where there is a slight disconnect, both relationships can be connected by a straight line as seen in

Figure 6. If samples begin to char early, reduce the maximum temperature being used. This test may have to be done using one treatment formulation at a time because each brand may have its own unique char initiation temperature.

Because there was no standard test found for the determination of density for comparison, this procedure may have certain limitations. One problem that was anticipated is the fact that MC will decrease with oven exposure time, but because density is desired at a range of temperatures, it is crucial to leave the specimens in the oven until the moment before they are weighed. Because water weight will have a significant on the overall weight, this presents a dilemma. Also, if the test is begun by equilibrating the specimens at 0%MC and 0%RH, this will negate any water weight effects, but the values of density will almost certainly not be representative of those seen in-service.

Thermal Inertia

Thermal inertia (the product of thermal conductivity, specific heat, and density) is one of the many parameters that can be derived from the use of a cone calorimeter. In the last few years, many countries have moved towards using a cone calorimeter for the measurement of the thermal characteristics of many combustible materials.

A material is exposed to a known radiant heat flux and by using the principle of oxygen consumption (13.1MJ of energy released per 1kg oxygen consumed for most solid materials), the cone calorimeter can measure its heat release rate. Other important values that can be measured are effective heat of combustion, total heat release, mass loss rate, time to ignition, and yield of combustion products among many others. Using equations shown in work by Grexa, et al. (Grex, et al 1996) and following a procedure

originally developed by Janssens (Janssens 1991), the thermal inertia, along with other important parameters such as total heat transfer coefficient, ignition temperature, and critical heat flux for ignition. A common procedure used to operate the cone calorimeter is described in the ISO 5660-1 standard test methods.

5.2 Thermal Degradation of FRTW in Fire Scenarios

One of the main modes of strength loss in wood materials is that of thermal degradation, as shown in this thesis. Though a model for this process has been developed for sawn lumber (White, et al. 1993), a similar model for FRTW has not yet been developed. As seen in this thesis, the thermal endurance model that was derived from published design factors for FRTW is inadequate since it does not represent the fire-robust behavior that FRTW has indeed been observed to exhibit. Through testing, a new model can be developed and applied, using the procedures in this project, to analyze FRTW as an alternative to the light-weight construction fire endurance issue that exists today.

This testing procedure is modeled after the experiments done by White, et al. (White, et al. 1993) in their paper entitled “Fire Endurance for a Metal-Plate-Connected Wood Truss”.

An apparatus capable of furnace testing and simultaneously loading the members in tension must be used for this procedure. Figure 13 shows the device that was used by White, et al. when developing the thermal degradation model for sawn lumber, which was used for analysis in this project. As seen in the photograph, the specially made tension apparatus was large enough to house the furnace. The furnace has dimensions of 7ft by 4.5ft and is lined with mineral fiber blankets. Heating is achieved via eight

diffusion-flame natural gas burners, six of which are spaced evenly along the 7ft dimension, three on each side. The remaining two burners are assumed to be at the bottom of the furnace, since they are not visible in any other location in the photograph. The lid of the furnace was removed in order to take the photograph.

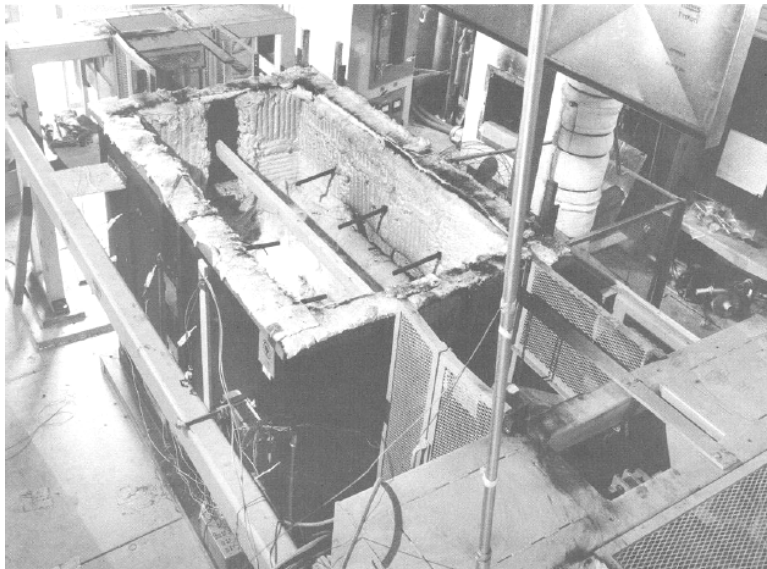


Figure 13: Photograph of testing tension/furnace apparatus used by White, et al. when their thermal degradation model was developed for sawn lumber (White, et al. 1993)

Because wood has such a low conductivity, thermal penetration takes much longer when using larger beams, and consequently will exhibit greater fire endurance. For this reason, testing should start by using nominal 2 by 4 members, as were the White, et al. tests (White, et al. 1993), but will be run using different sizes for confirmation of size effects once the model has been developed. Testing is to be done using 16ft nominal 2 by 4 members, equilibrated to 65%RH and 19%MC, with 6ft of the member exposed to heating. The member will be oriented with the wide side vertical. Elongation measurement can be taken using an extensometer system consisting of a reference arm that wraps around the furnace, a linear variable differential transducer (LVDT) at one

end, and clamps with magnetic attachment plates (White, et al. 1993). The strain gage length in White's experiments was around 11 ft.

Two types of tests are to be conducted: constant temperature with increased load until failure to develop the thermal degradation model, and then a constant load test with increased temperature to verify the model. Unloaded tests that determine temperature throughout the cross-section would allow development of the shape of the penetrated thermal boundary layer inside the wood.

The constant temperature testing would consist of heating the specimens in the furnace to temperatures of 100°C, 200°C, 250°C, 275°C, and 300°C for durations of 30 or 60 minutes in order to ensure even temperature distribution throughout the wood member. Two equilibration times are used simply for variation. Loading will be applied at a constant rate until failure to determine the maximum load as well as the load-elongation curve at a specified temperature.

Constant load tests will be loaded to the specimens 50% or 100% design load and exposed to fire until failure. Temperature in the furnace is to be controlled to follow the ASTM E-119 standard fire curve for verification of the model (704°C, 795°C, 843°C, 892°C, and 927°C at 10, 20, 30, 40, 50, and 60 minutes respectively), but further testing could be done using several types of fire curves such as high intensity, short duration or low intensity, long duration. The wood member will be instrumented to determine its temperature distribution for use in verifying the model. An idealized plenum time temperature curve was also used in the aforementioned experiment, derived from results for various actual ASTM tests, which was developed to represent the gas temperature at

the exposed surface of a member inside a protected assembly. This curve was 65°C, 93°C, 188°C, 260°C, and 327°C at 10, 20, 30, 40, 50, and 60 minutes respectively.

Once the data has been collected, the unloaded tests to determine the temperature profile in the wood can be used to develop a uniform temperature approximation while taking into account the shape of this profile. Once the representative temperature can be defined, the maximum capacity values from the constant temperature tests can be used to develop the strength degradation model. Results from the constant load tests will be used to verify and modify the model as needed.

This test is essential in the process to develop a realistic comparison between FRTW and sawn lumber in light-weight construction. As seen before, using the information that was available returned a model for strength degradation that wasn't representative of the nature of FRTW in fire conditions, showing the need for such an experiment to develop this information.

5.3 Char Progression in FRTW

Char is an essential part to the strength loss of timber members in a fire. FRTW chemically inhibits this process and eventually charring will actually cease. It is not clear what the critical char depth will be before combustion stops. One possible theory is that depending on the applied heat flux, the charring will reach a different level before enough insulation has built up to impede combustion. This theory indicates that greater heat fluxes will require thicker char layers to form before this can happen. To benchmark the char rate in relationship to exposure time, the proposed test method will use the ASTM E-119 fire curve first, before testing at a constant specified heat flux is performed.

Sample member sizes to be used are nominal 2 by 4 and 4 by 4 sections that are one to two feet long. Using the same sample sets described in Section 5.1 FRTW Thermophysical Properties when describing the proposed density test, equilibrate the specimens to 65%RH and 19%MC. Weigh all samples and then place in a furnace or oven equipped with temperature controlling devices capable of creating an environment that follows the ASTM E-119 test time/temperature profile. Take one specimen of each type out of the furnace after 15, 30, 60, 90, and 180 minutes of exposure. These increments are only speculative. The basis for choosing these times was to provide evenly distributed data over the exposure period. The user should adjust the increment times, or overall test duration, as they feel necessary. Weigh the specimens as they come out of the heating apparatus and referencing the densities derived from earlier tests, the volume of char can be identified. Char can be idealized as equal on all three, four, or six sides, depending how the specimens were exposed, and char thickness can be calculated. Also, the char layer is to be stripped from all faces of each specimen and final measurements taken for each affected dimension to compare to original dimensions to determine char thickness. Char thicknesses can be divided by the amount of time the sample was exposed to determine char rate in units of length per minute. It may be found that the exposure times noted here are not explicit enough to determine char rate since early in the process, FRTW will increase its char formation to quickly insulate the member, and then slow down considerably until it stops. If this is the case, use ten specimens for each FRTW formulation and take one sample out after 10, 15, 20, 25, 30, 45, 60, 90, 120, and 180 minutes. Increase in number of increments will provide more accurate results for the earlier char rate formation, which is the most critical in the

charring process for FRTW. Again, the increments chosen here are only speculative; therefore the user should adjust the increment times, or overall test duration, as they feel necessary.

5.4 Interaction of Wood Members and Truss Plates in Normal and Fire Scenarios

This testing procedure will develop an understanding of the change in wood/plate connection capacity in a fire scenario. This is integral in the development of a satisfactory model to accurately predict time to failure of a sawn lumber or FRTW truss assembly because this is one of the main failure mechanisms that has been observed.

The previously described tension/furnace should be used in these procedures as well so that loading and heat exposure can occur simultaneously. Similar procedures to the test for strength degradation will be used in this test as well, using the same member sizes and equilibration standards, but using FRTW as well as sawn lumber. This experiment however will need to capture three, possibly four different mechanisms: steel plate strength degradation when in contact with wood, tooth strength degradation, wood crushing, and possibly charring and its effects if 300°C isn't sufficient to determine the other three mechanisms.

A model for steel plate strength will be created in the same manner as the wood degradation model, using constant temperature and increased loading to determine maximum strength capacity values of each temperature and to create the model, followed by constant load tests with increasing temperature to verify and adjust the model. To capture the plate failure mechanism and ensure that tooth peeling does not occur, plates should be attached in normal fashion and then nailed to the specimens as well. Nails

should be placed at the extent of the plate and close to the member splice in a manner to ensure rupture will occur in the center of the plate, which is where it occurs in natural conditions (conditions without the added stiffness of the nails). This will allow the steel the added benefit of the heat sink the wood, but ensures plate rupture will be the mode of failure for each test.

Tooth stiffness and wood crushing under the teeth will have to be tested simultaneously since they both are contributing factors to the peeling failure. The same specimen size, equilibration standards, as well as the same two test types (constant temperature, constant load) are to be used as in the other experiments used to develop strength models. Plate tooth dimensions will be varied but must be designed so that the tooth capacity will be the ultimate limiting factor. This measure is crucial because if the tooth density is too high peeling will not occur and some other mode of failure, such as wood splitting or plate rupture, will occur first.

After testing to failure, critical tooth temperature, tooth angle, and size of the tooth penetration is to be measured. Tooth temperature can be referenced to the thermal degradation models for steel, which have been established and are discussed in Section 3.2 Strength Modeling, to determine if this was the limiting effect. Tooth critical angle should be measured and kept as reference to determine a critical deflection limit to be referenced later when categorizing the point of failure in truss plate connections. Tooth penetration holes will be measured and compared to tooth thickness (assumed as plate gauge thickness) to determine the critical wood crushing limit.

This combined mechanism can be modeled by analyzing the wood under the tooth as a compression member with a cross-section equal to the tooth face area, and with an

applied load equal to the individual tooth load. Because loading is applied normal to the tooth in its original state, wood crushing and tooth deflection will contribute to changing the direction of the reaction force to be still normal to the tooth face but now at an angle with the plate. Eventually the moment couple that is created from these deformations will overcome the bending capacity of the plate, and peeling will occur. Figure 14 shows a diagram that illustrates this progressive failure.

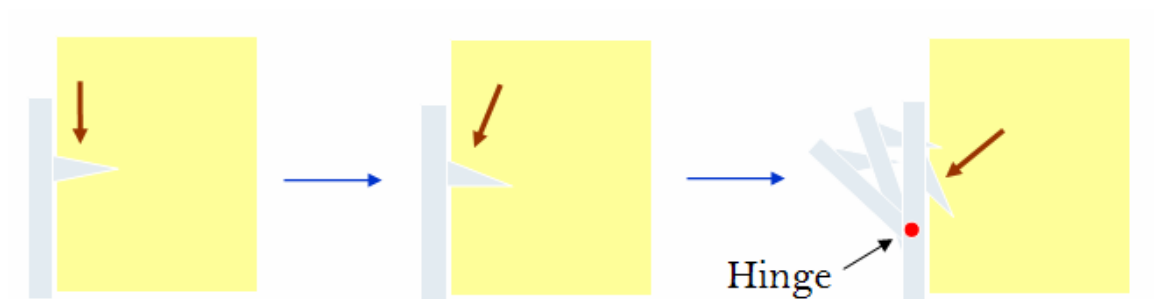


Figure 14: Theoretical sequence of events describing proposed progressive tooth withdrawal model

If temperatures over 300°C must be reached, char will inevitably form and need to be incorporated into the model as well. This could be accounted for by reducing the area for the compression member as char forms.

6.0 Conclusions

The purpose of this project was first to determine the time to collapse of sawn lumber and FRTW trusses, and second to extract relationships from the results to further advance the knowledge of the mechanisms for the collapse of wood trusses. These goals have been met but are limited by their inherent assumptions, which is a condition that is present in any theoretical work. This chapter summarizes the important relationships derived from this work, identifies considerations that have not been addressed and other limitations of this project, and offers final recommendations to further research in this subject.

The most valuable relationship taken from this analysis is the effect of the initial load to capacity ratio (ILCR) because this value essentially determined the mode of failure the truss would exhibit.

When the member ILCR was close to 1.0, much of the cross-section of the member was needed to carry the load for which it was designed. When only a small portion of this area was reduced via char and strength degradation, a member failure would occur before the connection became factor. This effect was heightened or diminished, depending on member orientation. If the member was modeled so that its major bending axis was aligned perpendicular to the direction of heat transfer, it took much longer for the critical area to be reached than if the member was modeled with the minor axis perpendicular to the direction of heat transfer since given the same char depth, much more area is lost for the later. This effect will become less prevalent on wood members as the difference between the cross-sectional dimensions becomes small.

Similarly, if the plate ILCR was close to 1.0, much of the capacity of the steel was utilized to transfer the axial loading from member to member. When only a small portion of the capacity was reduced via thermal degradation, a tooth deflection failure would occur before plate failure or member section loss could become a factor.

When the member and plate ILCR was both closer to 0.5, member and connection capacity were each possible limiting factors. It was noticed that if the plate ILCR was around 0.15 larger, or more, than the member ILCR, charring would lead to a tooth capacity failure. Alternatively, if the plate ILCR was closer than 0.15 to the member ILCR, the member would char and fail on its own before the connector teeth lost capacity.

In the case of the tooth capacity failure, less of the overall area of the wood member was needed to carry the loading, and charring was able to progress much further than if the member ILCR was closer to 1.0, allowing the char front to pass the first row of teeth, leaving an insufficient number of teeth to carry the loading. Though thermal strength degradation of steel was also incorporated into the analysis, charring had a much more significant effect on overall connection strength. Only horizontal members were used when including the possibility of connection failure because when compared to the endurance times listed for individual construction elements in the ASCE SFPE 29 99 specification, the times to failure for the vertical members were not compatible with the expected results. The tooth spacing on the truss plates chosen in this thesis only allowed three rows of teeth to be inserted in the 1.5 inch thickness of wood. This gave way to the recognition of a threshold connection failure time that relied on the char depth. Because only a few rows were carrying the loading, it became critical when one row's load

sharing capabilities was eliminated from the system. In this case, the residual tooth capacity was always insufficient, and failure was observed. Therefore, when member ILCR was around 0.5 the members could withstand significant section loss, but as soon as charring progressed past the first row of teeth, the residual tooth capacity wasn't sufficient to maintain integrity of the connection.

The final failure mode is that of plate rupture. Though it was not fully investigated due to the absence of a model to characterize temperature versus time for this element, its temperature was approximated as the average tooth temperature and included in the evaluation. From this analysis, using the scenario and information available, it is hypothesized that plate failure will be the last mode of failure exhibited, if the plate elements are satisfactorily designed. However, it also is hypothesized that if member ILCR is very small, and if thicker members are used to include multiple rows of teeth to ensure sufficient tooth capacity during significant charring, plate failure will govern.

When evaluating the time to failure including the possibility of connection failure, it was noticed that charring had a much more significant impact than thermal degradation. In this thesis the teeth were assumed to be at the same temperature as the wood it was in contact with. Using this assumption, it was found that the temperature of the connecting teeth were often well below any critical strength level. Though it can be assumed that the plate itself is slightly hotter than the teeth, since they are immersed in the insulating properties of wood, the tensile loading seen by the plate is transferred through significantly more material than the tooth loading. Therefore, it is hypothesized that when both member and plate ILCR are between 0.1 and 0.3, the wood has a significant

amount of section to withstand charring, and if thick members are used so that more rows of teeth are inserted in the section so that charring will not reduce the amount of effective teeth to a critical level, the connection plate will have sufficient time to heat up and fail via thermal degradation.

Another trend exhibited by this work is that insulation thickness will benefit overall fire endurance. This trend was expected since as thickness increases, so does thermal resistance, and by inspecting the finite difference model used in this thesis, it can be seen that the change in wood temperature will decrease as thermal resistance increases, delaying the process of thermal penetration.

Finally, the analysis in this thesis has shown that FRTW light-weight trusses will fail before sawn lumber trusses. This conclusion is not considered to be accurate because it is due in large part to the assumptions made when characterizing thermal degradation for FRTW products. Since the proposed thermal degradation model for FRTW was developed using published design adjustment factors, and because these factors are intended to be used for relatively low temperature, long duration environments when compared to a fire scenario, this model isn't representative of the type of situation evaluated herein and the results should not be interpreted directly. This model was a product of the fact that there is very limited information concerning the behavior of FRTW in actual fire scenarios. The work done in this thesis is just the first step in developing a comparative model between FRTW and sawn lumber trusses. More data needs to be collected so that it can be implemented into model such as the one used here and eventually verified with scale testing. This and several other important limitations are discussed further in the following section.

6.1 Limitations of the Work

Many assumptions had to be made to simplify this complex scenario. These assumptions have led to several limitations of this thesis that must be discussed.

Thermal analyses in this project involved developing and applying a one-dimensional finite difference model using the ASTM E-119 fire curve as the exposure conditions. These analyses are limited because they do not incorporate radiation heating from the interior surface of the gypsum in the plenum space to the vertical dimension of the exposed truss member. Inclusion of this mode of heat transfer would require a two dimensional model to be created.

Trusses in this work were designed by idealizing each member with pin-ended connections, allowing only axial loading to occur. In reality, some bending stresses will form in the members as well, creating the need for a combined stress index (CSI) for failure analysis. An example of the CSI used in the work by White, et al (1993) is described in Appendix A.8 Combined Stress Index.

Thermal expansion of the different materials in a truss will occur at different rates and because of this, residual stresses will accumulate. This effect has also been neglected during analysis.

When evaluating failure using thermal degradation of the wood member cross-section, the reduction value was chosen by the temperature in the foremost increment and used for the entire area. Because the remaining increments are at lower temperatures, each could be evaluated as having individual strength reduction values and a composite value could be created for a more accurate strength reduction evaluation. This type of analysis could easily add minutes onto the overall endurance rating by increasing the

capacity significantly in early stages, and then diminishing its impact as temperature profiles become closer together.

Finally, because the plate dimensions were assumed and not selected by a qualified manufacturer, and because a valid thermal analysis of the plate was not devised, plate temperature as a function of time was not well represented. The plate temperature was assumed to be the average of the tooth temperatures in order to develop a relationship with the other failure modes and with the initial design. This thesis also assumed that the maximum deflection limit for the connection teeth was 30% of the overall tooth length. Because this value was derived from simply inspecting photographs of peeling failures from previous tests, this value may be significantly skewed. However using these assumptions, a strong hypothesis that tooth deflection is the limiting mode of connection failure, has evolved from the test results, along with a the hypothesis char formation has greater impact on connection capacity than thermal degradation of steel.

6.2 In-Service Considerations

This section has been added to discuss possible installation practices and existing conditions that can affect how a truss assembly would behave under fire loading. End fixity, the use of furring channels, added connection measures due to the mistrust of truss plates, and ceiling protrusions are the issues that have been contemplated.

End conditions have been known to create many problems when attempting to model or test a structural system. The ASTM E-119 test attempts to incorporate some of this into their methods by using “restrained” or “unrestrained” end conditions depending on the connection type to be used when installed in the actual structure. This is significant because when structures are restrained during a fire, there is an added thrust

force due to thermal expansion acting on the structure to counteract the loading allowing the structure to have greater endurance. The trusses in this project were designed as if they were simply supported, pin-ended connections. When trusses are installed, they are placed on a bearing wall or foundation and bolted, nailed, or screwed into place, which in reality, none act as perfect pin ends or hinges. It is possible that all four extreme corners are connected to the structure, creating more of a fixed end than a pinned end, giving the structure more inherent load carrying capabilities, since three plastic hinges would need to form, instead of only one, to induce collapse.

Furring channels are used in many one-hour-rated construction assemblies using trusses. These steel channels are screwed to the underside of the trusses and the gypsum board is then attached to the channels rather than directly to the trusses themselves. This adds a few inches of insulating air separation between the inside surface of the ceiling gypsum and the truss members. However, because the use of furring channels is typically limited to structures that require rated structural assemblies, it is not generally found in residential construction, especially because of the added material costs that are not mandated by code.

Because light-weight truss construction has been known to fail suddenly in fire scenarios, some contractors have developed mistrust for the load carrying capabilities of this type of system, but still use it for its cost efficiency. Though they continue to utilize trusses, some have opted to insert extra nails into the connection plates to ensure that plates remain intact. This practice would certainly affect the behavior of the connections by effectively eliminating the possibility of tooth withdrawal. Also, by increasing the

overall connection stiffness, one of the most prevalent failure modes is eliminated, and surely time to failure will increase.

The final consideration was that of ceiling penetrations. This analysis was completed under the assumption that the gypsum board layer remains intact through the duration of the exposure. However, many common practices and phenomena can create pathways for the hot gasses from the room involved in fire to be transported into the truss plenum, dramatically increasing the temperatures seen by the exposed members. For older homes, foundation settling can cause cracking in the corners of a room; this cracking can propagate and, in the event of a fire, become a pathway for hot gasses. Previous water or fire damage in a home as well as normal wear and tear can break down the gypsum board and allow the fire to consume this layer faster and eventually expose the trusses. Lighting installations are simple mechanisms, present in every home that can act as ceiling protrusions in a fire. Not every type of lighting fixture is capable of being used in fire-rated construction, and almost certainly they are not used in most residential homes. Audio/visual equipment for home entertainment is another commonly installed component that may involve penetration of the ceiling. Another mechanical system that can transport hot gasses, not only into the plenum, but to other rooms, is the heating, ventilating and air conditioning system. Via either gaps around vent covers or the vent ducts themselves, hot gasses can travel through, and have a more profound effect on plenum temperatures if these systems are installed in the ceiling cavity. Finally, the quality of workmanship alone can determine whether the significance of ceiling penetrations have on the fire endurance of the floor/ceiling assemblies. If protrusions are sealed up tight with plaster, they may not have any affects, but if they are done poorly

and simply covered up with molding or other means, these penetrations may seriously decrease the ability of the ceiling to function as a barrier to a fire.

6.3 Recommendations for Future Research

The first recommendation to further this work would be to investigate the validity of the thermal analyses. FEM is a good type of model if concerned with one dimensional heat transfer and it could be used for comparison, but due to the complexity of the problem, a more in-depth FDM, that has the capability to integrate multiple dimensions and multiple modes of heat transfer relatively easily, would probably be the most beneficial. Addition of a radiation term that affects the vertical faces of the member would require at least a two-dimensional thermal model. A two-dimensional model would make it possible to categorize charring in both the vertical and lateral directions and also define a realistic time/temperature history for the face of the connector plate. This addition will also decrease the effect of member orientation on time to failure, since the two-dimensional heating would balance out the rate of section loss in each scenario.

Several types of natural fire exposures should also be considered for evaluation. Effects of long duration, low temperature, and short duration, high temperature fires, with a decay period, would add to the validity of the conclusions and to the determination if FRTW is a viable candidate to use in place of sawn lumber in light-weight truss construction.

Also, as described earlier in this chapter, bending and residual stresses are also present in trusses. Though they aren't completely understood under normal circumstances, they will inevitably have an impact on the time to failure of a truss and should be incorporated into the evaluation using a CSI.

Residual member capacity can also be evaluated as a composite cross-sectional area with strength reduction values unique to each increment at its own respective temperature. This will increase the durability of the members when compared to the data developed in this project because here, the strength of the entire cross-section was represented by the thermal degradation correction value associated with the highest temperature in the cross-section at any given time.

Designing the most economical plates for each scenario would also add validity to this work. This would allow evaluation using tooth densities, plate dimensions, and plate thicknesses, that are exactly what would be encountered had the system been designed for construction. Because the truss manufacturers are wholly responsible for the design of truss plates, research on how they are engineered will have to be completed as well. Currently the Truss Plate Institute publishes a publicly available design commentary that outlines, but does not go into detail on how to design each dimension of the truss plate. A separate FDM or FEM may also need to be developed to evaluate plate temperature in order to determine more accurately the point of plate shear rupture.

Finally, a probabilistic risk analysis could be done for determining if the special in-service considerations should be incorporated into this analysis to evaluate the impact of in-service conditions on structural fire performance of truss construction.

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Appendix

A.1 Product Specifications for Various Commercial FRTW Products

A1.1 PYRO-GUARD®

HOOVER TREATED WOOD PRODUCTS, INC.

TECHNICAL NOTE

FOR ADDITIONAL INFORMATION: 1-800-TEC-WOOD (832-9663)

SPECIFICATION GUIDE for *PYRO-GUARD*® Interior Fire Retardant Treated Wood

PART 1 – GENERAL

1.01 PRODUCT IDENTIFICATION

- A. All lumber and plywood specified to be interior fire retardant treated wood shall be pressure impregnated with *PYRO-GUARD*® which has a flame spread rating of 25 or less when tested in accordance with ASTM E 84, "Standard Test Method for Surface Burning Characteristics of Building Materials". *PYRO-GUARD*® fire retardant treated wood shall show no evidence of significant progressive combustion when the test is extended for an additional 20 minute period. In addition, the flame front shall not progress more than 10½ feet beyond the centerline of the burners at any time during the test.
- B. Fire retardant treated lumber and plywood shall be manufactured under the independent third party inspection of Underwriters Laboratories Inc. (UL) Follow-Up Service and each piece shall bear the UL classified mark indicating the extended ASTM E 84 test.
- C. Each piece shall be labeled kiln dried after treatment (KDAT). Timber Products Inspection, Inc. (TP) shall monitor the process and the TP mark shall appear on the label.

PART 2 – PRODUCTS

2.01 FIRE RETARDANT TREATMENT

- A. Treatment shall be *PYRO-GUARD*® manufactured by Hoover Treated Wood Products, Inc.
- B. Structural performance of fire retardant treated wood shall be evaluated in accordance with ASTM D 5664 for lumber and ASTM D 5516 for plywood. Evaluation of plywood data shall be in accordance with ASTM D 6305. The resulting design value and span rating adjustments shall be published in ICC Evaluation Service Report (ESR)-1791 issued by the ICC Evaluation Service, Inc. which includes evaluation of high temperature strength testing for roof applications.
- C. Interior fire retardant treated lumber and plywood shall have equilibrium moisture content of not over 28% when tested in accordance with ASTM D 3201 at 92% relative humidity.
- D. Interior fire retardant treated wood shall be kiln dried after treatment to a maximum moisture content of 19% for lumber and 15% for plywood.
- E. The fire retardant formulation shall be free of halogens, sulfates, chlorides, ammonium phosphate, and formaldehyde.
- F. Provide lumber of the appropriate grade and species as specified by the design criteria of the intended application after consideration of design value adjustments.
- G. Provide plywood of the appropriate size, grade and species as specified by the design criteria of the intended application after consideration of span rating adjustments.

2.02 PRODUCT SUBSTITUTION

No substitutions permitted.

PART 3 – EXECUTION

3.01 FIELD CUTS

- A. Lumber: Do not rip or mill fire retardant treated lumber. Cross cuts, joining cuts, and drilling holes are permitted.
- B. Plywood: Fire retardant treated plywood may be cut in any direction.

3.02 APPLICATION

- A. *PYRO-GUARD*® fire retardant treated lumber and plywood used in structural applications shall be installed in accordance with the conditions and limitations listed in ESR-1791 as issued by the ICC Evaluation Service, Inc.
- B. Treated wood shall not be installed in areas where it is exposed to precipitation, direct wetting, or regular condensation.
- C. Exposure to precipitation during shipping, storage and installation shall be avoided. If material does become wet, it shall be replaced or permitted to dry to a maximum moisture content of 19% for lumber and 15% for plywood prior to covering or enclosure by wallboard, roofing or other construction materials.

ICC Evaluation Service, Inc.
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Regional Office ■ 4051 West Flossmoor Road, Country Club Hills, Illinois 60478 ■ (708) 799-2305

DIVISION: 06—WOOD AND PLASTICS
Section: 06070—Wood Treatment

REPORT HOLDER:

HOOVER TREATED WOOD PRODUCTS, INC.
154 WIRE ROAD
THOMSON, GEORGIA 30824
(706) 595-7355
www.frtw.com

EVALUATION SUBJECT:

PYRO-GUARD® FIRE-RETARDANT-TREATED WOOD

ADDITIONAL LISTEES:

JASPER WOOD PRODUCTS, LLC
37385 JASPER LOWELL ROAD
JASPER, OREGON 97438

KILFOYLE KRAFTS
1510 SOUTH HIGHWAY 10
PRICE, UTAH 84501

1.0 EVALUATION SCOPE

Compliance with the following codes:

- 2003 *International Building Code*® (IBC)
- 2003 *International Residential Code*® (IRC)
- 1997 *Uniform Building Code*™ (UBC)
- BOCA® *National Building Code* 1999 (BNBC)
- 1999 *Standard Building Code*® (SBC)

Properties evaluated:

- Flame spread
- Structural strength
- Corrosion
- Hygroscopicity

2.0 USES

PYRO-GUARD® fire-retardant-treated wood is used in areas not exposed to the weather or wetting where the code permits the use of wood or fire-retardant-treated wood.

3.0 DESCRIPTION

3.1 General:

PYRO-GUARD® fire-retardant-treated wood is lumber and plywood that is pressure impregnated with the Hoover Treated Wood Products, Inc., fire retardant chemical PYRO-

GUARD®. PYRO-GUARD® fire-retardant-treated lumber and plywood is produced in accordance with an approved quality control procedure at facilities listed in Section 5.9 of this report.

PYRO-GUARD® treated lumber of the following species is recognized as being fire-retardant-treated wood: alpine fir, balsam fir, black spruce, Douglas fir, Englemann spruce, hem-fir, jack pine, lodgepole pine, ponderosa pine, red spruce, southern pine, spruce-pine-fir (SPF), western hemlock, white fir, and white spruce.

PYRO-GUARD® treated plywood fabricated with face and back veneers of the following species is recognized as being fire-retardant-treated wood: southern pine and Douglas fir for structural applications, and lauan for interior applications.

3.2 Flame Spread:

PYRO-GUARD® fire-retardant-treated wood, when tested in accordance with ASTM E 84 modified in accordance with Section 2303.2 of the IBC, has a flame-spread index of 25 or less.

3.3 Structural Strength:

The structural performance of PYRO-GUARD® fire-retardant-treated wood has been evaluated using ASTM D 5516 and D 6305 for plywood and ASTM D 5664 and D 6841 for lumber. The effects of the PYRO-GUARD® treatment on the strength of treated lumber shall be accounted for in the design of wood members and their connections. Load-duration factors greater than 1.6 shall not be used in design.

3.3.1 Lumber: The design value adjustments in Table 2 shall be used to modify the design values for untreated lumber found in the AF&PA National Design Specification (NDS) Supplement Design Values for Wood Construction, for the applicable species, use and property. Southern pine and Douglas fir have been evaluated for use in roof framing and shall be subjected to the adjustments indicated in Table 2 for roof framing. Other softwood species described in Section 3.1 shall be subjected to the design adjustments indicated in Table 2 for service temperatures up to 100°F (38°C).

3.3.2 Plywood: The maximum loads and spans shown in Table 1 shall be used to modify the panel span rating for untreated plywood described in the applicable codes, as determined by thickness and construction. The adjusted maximum loads and spans are based on tests of southern pine and Douglas fir and are applicable to all softwood species.

3.4 Corrosion:

The corrosion rate of aluminum, carbon steel, galvanized steel, copper or red brass in contact with wood is not increased by PYRO-GUARD® fire-retardant treatment when the product is used as recommended by Hoover Treated Wood Products.

ES REPORTS™ are not to be construed as representing aesthetics or any other attributes not specifically addressed, nor are they to be construed as an endorsement of the subject of the report or a recommendation for its use. There is no warranty by ICC Evaluation Service, Inc., express or implied, as to any finding or other matter in this report, or as to any product covered by the report.



3.5 Hygroscopicity:

The moisture content of PYRO-GUARD® fire-retardant-treated lumber and plywood is less than 28 percent when evaluated in accordance with ASTM D 3201 at 92 percent relative humidity (Section 2303.2.4 of the IBC). PYRO-GUARD® is suitable for use in interior conditions where sustained relative humidity is 92 percent or less and condensation does not occur.

4.0 DESIGN AND INSTALLATION

Structural systems that include PYRO-GUARD® fire-retardant-treated lumber or plywood shall be designed and installed in accordance with the applicable code using the appropriate lumber design value adjustment factors and plywood spans from Tables 1 and 2 of this report. Ventilation shall be provided in compliance with the applicable codes.

Fasteners used in PYRO-GUARD® fire-retardant-treated wood shall be hot-dipped zinc-coated galvanized steel, stainless steel, silicon bronze or copper, in accordance with IBC Section 2304.9.5, IRC Section R319.3, UBC Section 2304.3, and SBC Section 2306.3, and shall be subject to the design value adjustments indicated in Table 2 of this report.

5.0 CONDITIONS OF USE

The PYRO-GUARD fire-retardant-treated wood described in this report complies with, or is a suitable alternative to what is specified in, those codes listed in Section 1.0 of this report, subject to the following conditions:

- 5.1 All strength calculations shall be subject to the design factors or span ratings shown in Tables 1 and 2 of this report.
- 5.2 The strength design factors and span ratings given in this report shall only be used for unincised dimensional lumber and plywood of the species noted in this report.
- 5.3 All of the wood species listed in Section 3.1 of this report are permitted for interior applications and have been evaluated for structural performance for interior applications where the service temperature does not exceed 100°F (37.8°C). Southern pine and Douglas fir have been evaluated for structural performance for roof framing applications as indicated in Table 2 of this report. Southern pine and Douglas fir plywood are permitted for structural applications limited to the spans and loads indicated in Table 1 of this report.
- 5.4 PYRO-GUARD treated wood shall not be installed where it will be exposed to weather or damp or wet conditions.
- 5.5 PYRO-GUARD treated wood shall not be used in contact with the ground.
- 5.6 Except for the following, PYRO-GUARD lumber shall not be ripped or milled, as this may alter the surface-burning characteristics and invalidate the flame-spread classification: End cuts, holes, and joints such as tongue and groove, bevel, scarf and lap may be used.
- 5.7 Exposure to precipitation during storage or installation shall be avoided. If material does become wet, it shall be replaced or permitted to dry (maximum 19 percent moisture content for lumber and 15 percent moisture content for plywood) prior to covering or enclosure by wallboard or other construction materials (except for protection during construction).
- 5.8 The strength design factors and plywood spans in Tables 1 and 2 of this report are applicable under elevated temperatures resulting from cyclic climatic conditions in the continental United States. They are not applicable under continuous elevated temperatures resulting from manufacturing or other processes which shall require special consideration in design. Such conditions are outside the scope of this report.
- 5.9 Treatment is at the facilities of Hoover Treated Wood Products, Inc., in Thomson, Georgia, Pine Bluff, Arkansas, Milford, Virginia, Detroit, Michigan, and Winston, Oregon, and the Jasper Wood Products facility in Jasper, Oregon; and the Kilfoyle Krafts facility in Price, Utah; under a quality control program with inspections by Underwriters Laboratories Inc. (AA-668) and Timber Products Inspection Inc. (AA-696).

6.0 EVIDENCE SUBMITTED

Data in accordance with the ICC-ES Acceptance Criteria for Fire-retardant-treated Wood (AC66), dated November 2005.

7.0 IDENTIFICATION

Lumber and plywood treated with PYRO-GUARD® fire-retardant chemicals shall be identified by the structural grade mark of an approved agency. In addition, all treated lumber and plywood shall be stamped with the name of the inspection agency [Underwriters Laboratories Inc. (AA-668) or Timber Products Inspection Inc. (AA-696)], the Hoover Treated Wood Products, Inc., name and address, labeling information in accordance with Section 2303.2.1 of the IBC, and the evaluation report number (ESR-1791).

TABLE 1— MAXIMUM LOADS AND SPANS FOR PYRO-GUARD® TREATED PLYWOOD

PLYWOOD ⁹ THICKNESS (inches)	UNTREATED ROOF/SUBFLOOR SPAN RATING	PYRO-GUARD ^{6,1,2,3,4,5,8,11,12} ROOF SHEATHING MAX. LIVE LOAD (psf)				PYRO-GUARD ^{6,2,10} Span (Inches)
		Span (Inches)	Climate Zone ^{6,7}			
			1A	1B	2	
¹⁵ / ₃₂ , ¹ / ₂	32/16	24	19	30	43	16
¹⁹ / ₃₂ , ⁵ / ₈	40/20	24	42	64	87	20
		32	20	32	45	20
²³ / ₃₂ , ³ / ₄	48/24	32	34	51	71	24
		48	10	18	27	24
⁷ / ₈	—	48	12	20	30	—
¹ / ₈	—	48	21	33	47	48

For SI: 1 inch = 25.4 mm, 1 psf = 48 N/m².

¹All loads are based on two-span condition with panels 24 inches wide or wider, strength axis perpendicular to supports.

²Fastener size and spacing shall be as required in the applicable building code for untreated plywood of the same thickness; except that roof sheathing shall be fastened with (1) minimum 8d common or 8d deformed shank nails spaced a maximum 6 inches o.c. at edges and a maximum of 12 inches o.c. at intermediate supports for panels on 24- and 32-inch spans and spaced a maximum of 6 inches o.c. on all supports for panels on a 48-inch span, or (2) other fasteners with comparable withdrawal and lateral load capacities at the same maximum spacings. For ¹/₈-inch roof sheathing panels, use minimum 10d common or deformed shank nails.

³Roof spans and loads apply to roof systems having the minimum ventilation areas required by the applicable building code. Fifty percent of required vent area shall be located on upper portion of sloped roofs to provide natural air flow.

⁴For low-sloped or flat roofs with membrane or built-up roofing having a perm rating less than 0.2, use rigid insulation having a minimum R value of 4.0 between sheathing and roofing, or use next thicker panel than tabulated for the span and load (e.g., ¹⁹/₃₂ for 24 inches, ²³/₃₂ for 32 inches); and use a continuous ceiling air barrier and vapor retarder with a perm rating less than 0.2 on the bottom of the roof framing above the ceiling finish.

⁵Panel edge clips are required for roof sheathing: one midway between supports for 24-inch and 32-inch spans, two at ¹/₃ points between supports for 48-inch span. Clips shall be specifically manufactured for the plywood thickness used.

⁶Tabulated loads for Zone 1A are based on a duration of load adjustment for 7-day (construction) loads of 1.25. Tabulated loads for Zone 1B and Zone 2 are based on a duration of load adjustment for snow of 1.15. All values within the table are based on a dead load (DL) of 8 psf. If the DL is less than or greater than 8 psf, the tabulated live load shall be increased or decreased by the difference. Applicable material weights, psf: asphalt shingles - 2.0, ¹/₂-inch plywood - 1.5, ⁵/₈-inch plywood - 1.8, ³/₄-inch plywood - 2.2.

⁷Climate Zone definition:

- 1 - Minimum design roof live load or maximum ground snow load up to 20 psf:
 - A - Southwest Arizona, Southeast Nevada (Las Vegas-Yuma-Phoenix-Tucson triangle)
 - B - All other qualifying areas of the continental United States
- 2 - Minimum ground snow load over 20 psf

⁸PYRO-GUARD® treated plywood shall not be used as roof sheathing if a radiant shield is used beneath the roof sheathing.

⁹The ¹⁹/₃₂-inch and ⁵/₈-inch thickness are limited to performance rated 4-ply or 5-ply. ²³/₃₂- and ³/₄-inch thicknesses are limited to performance rated 5-ply or 7-ply.

¹⁰Subfloor applications are limited to 100 psf maximum live load, except ¹/₈-inch thickness on 48-inch span limited to 65 psf total load.

¹¹Deflection of roof sheathing at tabulated maximum live load is less than ¹/₂₄₀ of the span, and under maximum live load plus dead load is less than ¹/₁₈₀ of the span.

¹²Staples used to attach asphalt shingles shall be minimum ¹⁹/₁₆-inch crown and minimum 1-inch leg, or otherwise comply with the applicable code, with the quantity of fasteners adjusted in accordance with Table 2 of this report.

TABLE 2—DESIGN VALUE ADJUSTMENTS FOR PYRO-GUARD® TREATED LUMBER

PROPERTY	SERVICE TEMPERATURE ⁶ TO 100°F/38°C			PYRO-GUARD® ROOF FRAMING, CLIMATE ZONE ^{1,2,5}					
	SP	DF	Other	1A		1B		2	
				SP	DF	SP	DF	SP	DF
Extreme fiber in bending	0.91	0.97	0.88	0.80	0.90	0.85	0.93	0.89	0.96
Tension parallel to grain	0.88	0.95	0.83	0.80	0.80	0.84	0.87	0.88	0.93
Compression parallel to grain	0.94	1.00	0.94	0.94	0.94	0.94	0.98	0.94	1.00
Horizontal shear	0.95	0.96	0.93	0.92	0.95	0.93	0.95	0.94	0.96
Modulus of elasticity	0.95	0.96	0.94	0.95	0.96	0.95	0.96	0.95	0.96
Compression perp. to grain	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Fasteners/connectors	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90

¹Climate Zone definition:

- 1 - Minimum design roof live load or maximum ground snow load up to 20 psf:
 - A - Southwest Arizona, Southeast Nevada (Las Vegas-Yuma-Phoenix-Tucson triangle)
 - B - All other qualifying areas of the Continental United States
- 2 - Minimum ground snow load over 20 psf


²Duration of load adjustments for snow loads, 7-day (construction) loads, and wind loads given in the National Design Specifications for Wood Construction apply.

³Where lumber decking serves as both exposed ceiling and roof sheathing, use extreme fiber in bending adjustments of 0.84, 0.83, and 0.89 for southern pine zones 1A, 1B, and 2, respectively; 0.92, 0.92, and 0.96 for Douglas fir zones 1A, 1B, and 2, respectively; except that where insulation having a minimum R value of 4.0 is installed above the decking, extreme fiber in bending adjustments of 0.91 for southern pine and 0.97 for Douglas fir are permitted in all zones.

⁴Modulus of elasticity values apply to all treated lumber decking.

⁵Roof framing adjustment factors apply to roof systems with minimum ventilation areas per applicable code. Locate 50 percent of required vent area on upper portion of sloped roofs to provide natural air flow.

⁶Species: SP - southern pine; DF - Douglas fir; Other softwoods - limited to those species listed in Section 3.1 of this report.

<p>PYRO-GUARD® — HOOVER — TREATED WOOD PRODUCTS INC. (PLANT LOCATION) PROCESS CONTROL STANDARD 2200P MONITORED BY TP</p>	<p><small>CLASSIFIED</small>  TREATED LUMBER 15P9 R7002</p> <p>SPECIES SURFACE BURNING CHARACTERISTICS FLAMESPREAD: SMOKE DEVELOPED:</p> <p>30 MINUTE TEST</p>
KDAT ICC-ESR-1791 MEA-359-88-M KDAT	


<p>PYRO-GUARD® — HOOVER — TREATED WOOD PRODUCTS INC. (PLANT LOCATION) PROCESS CONTROL STANDARD 2200P MONITORED BY TP</p>	<p><small>CLASSIFIED</small>  TREATED PLYWOOD 17PO R7003</p> <p>SPECIES SURFACE BURNING CHARACTERISTICS FLAMESPREAD: SMOKE DEVELOPED:</p> <p>30 MINUTE TEST</p>
KDAT ICC-ESR-1791 KDAT	

FIGURE 1—LUMBER AND PLYWOOD STAMPS

A1.2 EXTERIOR FIRE-X®

HOOVER TREATED WOOD PRODUCTS, INC.

TECHNICAL NOTE

FOR ADDITIONAL INFORMATION: 1-800-TEC-WOOD (832-9663)

SPECIFICATION GUIDE FOR EXTERIOR FIRE-X® Exterior Fire Retardant Treated Wood

PART 1 – GENERAL

1.01 PRODUCT IDENTIFICATION

- A. All lumber and plywood designated to be exterior fire retardant treated shall be pressure impregnated with **EXTERIOR FIRE-X®** which has a flame spread rating of 25 or less when tested in accordance with ASTM E 84, “Standard Test Method for Surface Burning Characteristics of Building Materials”. **EXTERIOR FIRE-X®** fire retardant treated wood shall show no evidence of significant progressive combustion when the test is extended for an additional 20 minute period. The flame front shall not progress more than 10½ feet beyond the centerline of the burners at any time during the test.
- B. In addition, there shall be no increase in the listed classification when tested after ASTM D 2898 “Standard Test Methods for Accelerated Weathering of Fire-Retardant-Treated Wood for Fire Testing.”
- C. Fire retardant treated lumber and plywood shall be manufactured under the independent third party inspection of Underwriters Laboratories Inc. (UL) Follow-Up Service and each piece shall bear the UL classified mark indicating the extended ASTM E 84 test.
- D. Each piece shall be labeled kiln dried after treatment (KDAT). Timber Products Inspection, Inc. (TP) shall monitor the process and the TP mark shall appear on the label.
- E. Optional pressure applied blue stain for easy identification.

PART 2 – PRODUCTS

2.01 FIRE RETARDANT TREATMENT

- A. Treatment shall be **EXTERIOR FIRE-X®** manufactured by Hoover Treated Wood Products, Inc.
- B. All exterior fire retardant treated wood shall be kiln dried after treatment to a maximum moisture content of 19% for lumber and 15% for plywood.
- C. Kiln drying after treatment shall be monitored by Timber Products Inspection, and the identification label on each piece of wood shall so indicate.
- D. Exterior fire retardant treated lumber and plywood shall use design value adjustments and span ratings as published by the manufacturer.
- E. The fire retardant formulation must be free of halogens, sulfates, chlorides, and ammonium phosphate.
- F. Provide lumber of the appropriate grade and species as specified by the design criteria of the intended application.
- G. Provide plywood of the appropriate size, grade and species as specified by the design criteria of the intended

2.02 PRODUCT SUBSTITUTION

No substitutions permitted.

PART 3 – EXECUTION

3.01 FIELD CUTS

- A. Lumber: Do not rip or mill fire retardant treated lumber. Cross cuts, joining cuts, and drilling holes are permitted.
- B. Plywood: Fire retardant treated plywood may be cut in any direction.

3.02 APPLICATION

- A. **EXTERIOR FIRE-X®** fire retardant treated lumber and plywood used in structural applications shall be applied according to the lumber and plywood strength tables provided by the manufacturer.
- B. **EXTERIOR FIRE-X®** is a non-leachable fire retardant treatment and may be installed with direct exposure to precipitation; however, it cannot be substituted for preservative treated wood.

AFX-Spec 11/05

EXTERIOR FIRE-X[®]

FIRE RETARDANT TREATED LUMBER AND PLYWOOD ENGINEERING DATA

The following design value adjustments and plywood span ratings should be utilized for EXTERIOR FIRE-X:

DESIGN VALUE ADJUSTMENTS FOR EXTERIOR FIRE-X LUMBER

The adjustments tabulated below apply to EXTERIOR FIRE-X fire retardant treated southern pine lumber which bears the grademark of an ALS approved lumber grading or inspection agency and is used in the following conditions of service:

- A. In non-roof system applications where the ambient temperature does not exceed 125° F. **OR**
- B. As framing members in roof systems where
 - (1) Lumber temperature does not exceed 150° F; and
 - (2) Ventilation is evenly distributed, provides a uniform air flow over all interior roof surfaces, and is sufficient to effectively remove moisture when the roof system is warmed by solar radiation.

Property	Adjustment Factor
Extreme fiber in bending	.85
Tension parallel to grain	.80
Horizontal shear	.90
Compression perpendicular to grain	.90
Compression parallel to grain	.90
Modulus of elasticity	.90
Fastener/connector design loads	.90

For special applications where structural members may exceed a temperature of 150° F. contact Hoover Treated Wood Products, Inc. at 800/TEC-WOOD or 706/595-5058.

SPAN RATINGS FOR EXTERIOR FIRE-X PLYWOOD

The following plywood roof sheathing and subfloor spans apply to span-rated plywood and/or plywood bearing the trademark of an approved inspection agency, treated with EXTERIOR FIRE-X fire retardant where roof system ventilation is evenly distributed, provides a uniform air flow over all interior roof surfaces, and is sufficient to effectively remove moisture when the roof system is warmed by solar radiation.

Panel Thickness (in.)	Untreated Span Index Rating	Exterior Fire-X Max. span (in.)	
		Roof Sheathing (1, 2, 3, 5)	Subfloor (2)
11/32, 3/8	24/0	—	—
15/32, 1/2	32/16	24	16
19/32, 5/8	40/20	32	20
23/32, 3/4	48/24	40	24
7/8 (4)	—	48	24

- (1) Clips, blocking or other edge supports must be used with roof sheathing.
- (2) Maximum roof load: 10 psf DL, plus 40 psf LL Maximum floor load: 10 psf DL, plus 100 psf LL
- (3) For flat roof applications, call Hoover Treated Wood Products, Inc. at 800/TEC-WOOD or 706/595-5058.
- (4) Limited to 7/8" CDX plywood made with Group 1 species.
- (5) EXTERIOR FIRE-X treated plywood shall not be used in roof designs employing a radiant shield that is located underneath the bottom surface of the sheathing.

NOTE: THESE SPAN RATINGS ARE BASED ON TEST RESULTS FOR EXTERIOR FIRE-X TREATED PLYWOOD AFTER EXTENDED EXPOSURE TO ELEVATED TEMPERATURES AND MOISTURE.

HOOVER
TREATED WOOD PRODUCTS, INC.
P.O. Box 746, Thomson, Georgia 30824 / (706) 595-5058



11/96 <http://www.HooverFRTW.com>



National Evaluation Service, Inc.

5203 Leesburg Pike, Suite 600, Falls Church, Virginia 22041-3401

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NATIONAL EVALUATION REPORT

Report No. NER-303

Re-Issued April 1, 2002

DIVISION 06 – WOOD AND PLASTICS

Section 06320 – Fire Retardant Treatment

REPORT HOLDER:

ARCH WOOD PROTECTION, INC.
1955 LAKE PARK DRIVE
SUITE 250
SMYRNA, GEORGIA 30080
www.dricon.com

EVALUATION SUBJECT:

DRICON® FIRE RETARDANT TREATED
WOOD

Listings:

D-40	Arizona Pacific Wood Preserving Inc.	Eloy, AZ
D-22	Biewer Lumber Co.	Seneca, IL
D-42	Biewer Lumber of Lansing LLC	Lansing, MI
D-37	Cleveland Wood Preserving	Cleveland, OH
D-3	Consumers Wood Preserving Co.	West Elizabeth, PA
D-2	Cox Wood Preserving Co.	Orangeburg, SC
D-17	Dean Lumber Co.	Gilmer, TX
D-43	Everwood Treatment Co.	Spanish Ft., AL
D-28	Exterior Wood, Inc.	Washougal, WA
D-41	Mid-States Wood Preservers, Inc.	Simboro, LA
D-38	Northeast Treaters of NY, LLC	Athens, NY
D-39	Pacific Wood Preserving	Bakersfield, CA
D-30	Quality Wood Treating Co.	Prairie du Chien, WI
D-35	Southern Wood Treatment	Winchester, KY
D-1	Shaw/Stewart Lumber Co.	Minneapolis, MN
D-32	Trent Timber Treating, Ltd.	Peterborough, ONT
D-23	Utah Wood Preserving Co.	Woods Cross, UT
D-31	Wood Preservers Inc.	Warsaw, VA

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This report is limited to the specific product and data and test reports submitted by the applicant in its application requesting this report. No independent tests were performed by the National Evaluation Service, Inc. (NES), and NES specifically does not make any warranty, either expressed or implied, as to any finding or other matter in this report or as to any product covered by this report. This disclaimer includes, but is not limited to, merchantability. This report is also subject to the limitation listed herein.

**NATIONAL
EVALUATION
SERVICE, INC.**

NES
Product Evaluation Listing

1.0 SUBJECT

**2.0 PROPERTIES FOR WHICH
EVALUATION IS SOUGHT**

3.0 DESCRIPTION

4.0 INSTALLATION

5.0 IDENTIFICATION

6.0 EVIDENCE SUBMITTED

7.0 CONDITIONS OF USE

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1.0 SUBJECT

- 1.1 Dricon® Fire Retardant Treated Wood

2.0 PROPERTIES FOR WHICH EVALUATION IS SOUGHT

- 2.1 Flame Spread
2.2 Structural Durability
2.3 Corrosion
2.4 Hygroscopicity

3.0 DESCRIPTION

3.1 General

Dricon® Fire Retardant Treated Wood is lumber and plywood impregnated with Dricon fire retardant chemicals by a pressure process. Dricon fire-retardant-treated wood shall be used in areas not exposed to the weather or wetting where the applicable code permits the use of wood or fire-retardant-treated wood.

Dricon treatment of lumber of the following species is recognized as being fire retardant:

Douglas Fir	Spruce-Pine-Fir
Redwood	Spruce
White Pine	Ponderosa Pine
Hem Fir	Western Red Cedar
Southern Pine	White Fir
Red Pine	Western Hemlock

Dricon treatment of plywood fabricated with face and back veneers of the following species is recognized as being fire retardant:

Southern Pine Douglas Fir Spruce-Pine-Fir

3.2 Flame Spread

Dricon fire retardant treated wood has a flame-spread rating of 25 or less when subjected to ASTM E84 tests of 30 minute duration without evidence of significant progressive combustion.

3.3 Structural Durability

The structural durability of Dricon fire retardant treated lumber and plywood has been investigated resulting in the development of design values and span adjustments to modify the untreated design values for lumber and span ratings for plywood.

The strength properties of lumber when treated with Dricon fire retardant chemicals and used in applications at ambient temperatures up to 80° F., are subject to the design factors shown in [Table 1](#) of this report.

The strength properties of lumber, when treated with Dricon fire retardant chemicals and used in applications at elevated temperatures up to 150° F., are subject to the design factors shown in [Table 2](#) of this report.

The strength properties of plywood, when treated with Dricon fire retardant chemicals and used in applications at temperatures up to 170° F., are subject to the span limitations shown in [Table 3](#) of this report.

3.4 Corrosion

The corrosion rate of aluminum, carbon steel, galvanized steel, copper or red brass in contact with wood is not increased by Dricon fire retardant treatment when the product is used as recommended by the manufacturer.

Fasteners used in Dricon fire retardant treated lumber and plywood shall be galvanized steel, stainless steel, silicon bronze, copper or other suitable corrosion-resistant material.

**NATIONAL
EVALUATION
SERVICE, INC.**

**NES
Product Evaluation Listing**

1.0 SUBJECT

**2.0 PROPERTIES FOR WHICH
EVALUATION IS SOUGHT**

3.0 DESCRIPTION

4.0 INSTALLATION

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6.0 EVIDENCE SUBMITTED

7.0 CONDITIONS OF USE

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3.5 Hygroscopicity

Dricon treated wood is an Interior Type A (HT) fire-retardant wood in accordance with the American Wood-Preservers' Association Standards C20 and C27. Dricon treated Douglas fir, Southern pine and Spruce-pine-fir lumber and Douglas fir, Southern pine and Spruce-pine-fir plywood qualify as Interior Type A (HT) fire retardant treated wood when tested at 95 percent relative humidity.

4.0 INSTALLATION

Structural systems which include Dricon fire retardant treated lumber or plywood shall be designed and installed in accordance with the applicable code using the appropriate lumber design value adjustment factors and plywood spans from Tables 1, 2 and 3 of this report. Ventilation shall be provided in compliance with the applicable codes.

5.0 IDENTIFICATION

All lumber and plywood treated with Dricon fire retardant chemicals shall be identified by the grade mark of an approved agency. All lumber and plywood shall, in addition, bear the Underwriters Laboratories Inc. and Timber Products Inspection label, the producing plant identification, the flame-spread rating or FR-S designation and NER-303 for field identification (see [Figure 1](#) of this report).

6.0 EVIDENCE SUBMITTED

- 6.1** Test report in accordance with ASTM D3201, Hygroscopic Properties of Fire Retardant Wood and Wood Based Products on Dricon® Fire Retardant Treated Lumber, prepared by Underwriters Laboratories Inc., File R2805, Project 84NK-29476 dated March 29, 1985.
- 6.2** Test report in accordance with ASTM D3201, Hygroscopic Properties of Fire Retardant Wood and Wood Based Products on Dricon® Fire Retardant Treated Plywood, prepared by Underwriters Laboratories Inc., File R3718, Project 84NK-29476 dated March 29, 1985.
- 6.3** Test reports prepared by Koppers Company, Inc., as witnessed by Pittsburgh Testing Laboratory, Project 83-ST-059 dated April 5, 1984, testing in accordance with:
- ASTM D143, Method of Testing Small Clear Specimens of Timber.
 - ASTM D3043, Method of Testing Plywood in Flexure.
 - ASTM D3501, Method of Testing Plywood in Compression.
 - ASTM D2718, Method of Testing Plywood in Rolling Shear (shear in plane of plies).
 - AWWA C20, Structural Lumber Fire Retardant Treatment by Pressure Process.
 - AWWA C27, Plywood Fire Retardant Treatment by Pressure Process.
 - Military Specifications MIL-0019140D(SH), Lumber and Plywood, Fire Retardant Treated.
- 6.4** Test report in accordance with ASTM E84, Surface Burning Characteristics of Building Materials for Dricon® Fire Retardant Treated Lumber, prepared by Underwriters Laboratories Inc., File R2805, Projects 83NK18126 dated October 26, 1984, and 79NK1298 dated February 25, 1981.
- 6.5** Test report in accordance with ASTM E84, Surface Burning Characteristics of Building Materials for Dricon® Fire Retardant Treated Plywood, prepared by Underwriters Laboratories Inc., File R3718, Project 79NK1298 dated March 3, 1981.
- 6.6** Test report conducted using the Factory Mutual construction materials calorimeter to determine the rate of fuel contribution for Dricon® fire retardant treated lumber, prepared by Factory Mutual Research, Report OF7A4.AM(4950) dated December 23, 1981.
- 6.7** Test report in accordance with ASTM D1413, Method of Testing Wood Preservatives by Laboratory Soil-block Cultures, for Dricon® Fire Retardant Treated Wood, prepared by Michigan Technological University, Institute of Wood Research dated January 4, 1984.

**NATIONAL
EVALUATION
SERVICE, INC.**

**NES
Product Evaluation Listing**

1.0 SUBJECT

**2.0 PROPERTIES FOR WHICH
EVALUATION IS SOUGHT**

3.0 DESCRIPTION

4.0 INSTALLATION

5.0 IDENTIFICATION

6.0 EVIDENCE SUBMITTED

7.0 CONDITIONS OF USE

[back to the NES home page](#)

- 6.8** Test report on The Bending and Stiffness Properties of Dricon® Fire Retardant Treated Plywood after Exposure to Elevated Temperature and Humidity, in accordance with the August 1988 NFPA proposed protocol for testing FRT plywood, conducted at the College of Agriculture, University of Illinois dated September 18, 1989, signed by Poo Chow, Ph.D. This report was reviewed by Robert F. Robins, P.E., F.P.E.
- 6.9** Structural calculations evaluating temperature test data to produce plywood roof span tables, prepared by Kidde Consultants, Inc., dated April 28, 1989, signed and sealed by A. Rhett Whitlock, Ph.D., P.E.
- 6.10** Structural evaluation of floor spans based on ambient temperature data to produce floor span tables, prepared by GFDS Engineers dated February 21, 1989, signed by Edward F. Diekmann, S.E.
- 6.11** Underwriters Laboratories Inc. Follow-up Service Procedures, File R3718, Volume 5, Issued January 5, 1990, revised 03/14/2001, for treated plywood and File R2805, Volume 9, Issued December 22, 1989, revised 03/14/2001, for treated lumber.
- 6.12** Engineering review of properties for Fire-retardant-treated Lumber, prepared by Law Engineering, Project 5620114302 dated February 25, 1991, signed by Michael B. Merrick, P.E., and Robert S. Jenkins, P.E.
- 6.13** Engineering review of plywood standard for FRTW, prepared by Robins Boldso, Inc., dated November 17, 1990, signed and sealed by Robert F. Robins, P.E.
- 6.14** Arch Wood Protection, Inc. *Standard D-1 Process Monitoring Program for Dricon Fire Retardant Treated Wood, 12/13/01*, signed by representatives of Arch Wood Protection, Inc. and the third party inspection agency, Timber Products Inspection, Inc., 12/14/01.

7.0 CONDITIONS OF USE

The National Evaluation Service Committee finds that Dricon® Fire Retardant Treated Wood complies with or is a suitable alternate to that described in the *2000 International Building Code with 2001 Supplement*, the *BOCA National Building Code/1999*, the *1999 Standard Building Code*, the *1997 Uniform Building Code*, the *2000 International Residential Code for One- and Two-Family Dwellings with the 2001 Supplement*, and the *1998 International One and Two Family Dwelling Code* subject to the following conditions:

- 7.1** All strength calculations are subject to the design factors or span ratings shown in Tables 1, 2 and 3 of this report.
- 7.2** The strength design factors and span ratings given in this report are only used for unincised dimensional lumber and plywood of the species noted in this report.
- 7.3** The treated lumber and plywood are only used in areas (including attic spaces) where the lumber is exposed to temperatures of 150° F. or less and the plywood is exposed to temperatures of 170° F. or less.
- 7.4** Dricon wood shall not be installed where it will be exposed to precipitation, direct wetting or regular condensation.
- 7.5** Dricon wood shall not be used in contact with the ground.
- 7.6** Except as listed below, Dricon lumber shall not be ripped or milled as this will alter the surface-burning characteristics and invalidate the flame-spread classification:
- Western red cedar lumber may be surfaced 1/32 inch;
 - Framing, end cuts, holes, joints such as tongue and groove, bevel, scarf and lap may be used.

- 7.7 Exposure to precipitation during shipping, storage or installation shall be avoided. If material does become wet, it shall be replaced or permitted to dry (maximum 19 percent moisture content for lumber and 15 percent moisture content for plywood) prior to covering or enclosure by wallboard or other construction materials (except for protection during construction).
- 7.8 The strength design factors and plywood spans in Tables 2 and 3 of this report are applicable under elevated temperatures resulting from cyclic climatic conditions. They are not applicable under continuous elevated temperatures resulting from manufacturing or other processes which shall require special consideration in design, which is not within the scope of this report.
- 7.9 This report is subject to periodic re-examination. For information on the current status of this report, consult the NES Product Evaluation Listing or contact the NES.

Table 1
Strength Design Factors
Dricon® Fire Retardant Treated
Lumber Compared to Untreated Lumber
Applicable At Temperatures Up to 80° F.

		Tested Species			Other Species
		Southern Pine	Douglas Fir	Spruce	
Compression Parallel, Fc		0.94	0.91	0.95	0.91
Horizontal Shear		0.95	0.94	0.95	0.94
Tension Parallel		0.92	0.87	0.98	0.87
Bending: Modulus of Elasticity, E		0.98	0.98	0.98	0.98
Extreme Fiber Stress, Fb		0.89	0.90	0.98	0.89
FASTENERS/CONNECTORS					
Nails	Withdrawal	0.91	0.91	1.0	0.91
	Lateral	0.98	0.98	1.0	0.98
Wood Screws	Withdrawal	0.94	0.94	1.0	0.94
Bolted Joints	Parallel to Grain	0.92	0.92	1.0	0.92
	Perpendicular to Grain	0.96	0.96	1.0	0.96

Table 2

**Strength Design Factors
Dricon® Fire Retardant Treated
Lumber Compared to Untreated Lumber**

Applicable At Temperatures Up to 150° F.

	Tested Species			Other Species
	Southern Pine	Douglas Fir	Spruce	
Compression Parallel, Fc	0.67	0.65	0.67	0.65
Horizontal Shear	0.69	0.67	0.69	0.67
Tension Parallel	0.85	0.80	0.85	0.80
Bending: Modulus of Elasticity, E	0.91	0.91	0.91	0.91
Extreme Fiber Stress, Fb	0.80	0.80	0.80	0.80

Table 3

**Dricon® Plywood Span Ratings
For Rated Sturd - I - Floor and Rated Sheathing**

Applicable At Temperatures Up to 170° F.

APA Rating	Panel Thickness*	DRICON Rating
12/0	5/16	12/0
16/0	5/16, 3/8	16/0
20/0	5/16, 3/8	20/0
24/0	3/8, 7/16, 1/2	24/0
24/16	7/16, 1/2	24/16
32/16	15/32, 1/2	24/16
32/16	5/8	32/16
40/20	5/8, 19/32	32/20
40/20	3/4, 7/8	40/20
48/24	23/32, 3/4	40/24
48/24	7/8	48/24

Gluelines shall be exterior and face plies shall be Group I species noted in Section 3.1 of this report. Allowable uniformly distributed live load at maximum span for RATED STURD-I-FLOOR and RATED SHEATHING is 85 psf for floors (55 psf for STURD-I-FLOOR 48 oc) and 30 psf for roofs plus 8.5 psf dead load in each case.

*Arch Wood Protection, Inc. does not recommend 5/16 or 3/8 panel thicknesses for roofing applications.



FIGURE 1

NOTES TO FIGURE1:

In place of the FR-S designation, the flame spread and smoke developed ratings for the species are permitted to be shown.

The plant identification number shall be permitted in place of the treating company name and plant location.

All lumber and plywood shall be identified by the grade mark of an approved agency.

A1.4 D-Blaze®



FIRE RETARDANT TREATMENT 06073

Chemical Specialties, Inc.



1. Product Name

D-Blaze® Fire Retardant Pressure Treated Wood

2. Manufacturer

Chemical Specialties, Inc. (CSI)
One Woodlawn Green, Suite 350
200 East Woodlawn Road
Charlotte, NC 28217
(800) 421-8661
(704) 522-0825

Fax: (704) 527-8232

E-mail: productinfo@chemspec.com
www.treatedwood.com

3. Product Description

BASIC USE

D-Blaze® Fire Retardant Treated (FRT) lumber and plywood is highly effective against the spread of flame and smoke in weather protected applications. It can be used where building codes permit the use of wood or fire retardant treated wood. Recommended and typical uses include roof trusses, roof decks and sheathing, beams and purlins, floor trusses, subflooring, joists, interior non-load bearing partitions, exterior load-bearing walls, studs, architectural millwork and trim, blocking and furring, and paneling.

COMPOSITION & MATERIALS

D-Blaze is pressure treated deep into the wood; it is not a coating. D-Blaze is noncorrosive. Wood species, which qualify under UL FRS classification, include a variety of softwood lumber, plywood and hardwood lumber.

TYPES

Softwood lumber

- Alpine fir
- Black spruce
- Douglas fir
- Jack pine
- Ponderosa pine
- Red spruce
- Spruce-pine-fir
- White fir
- Balsam fir
- Englishman spruce
- Hem-fir
- Lodgepole pine
- Red pine
- Southern yellow pine
- Western hemlock
- White spruce

Plywood

- Douglas fir
- Red pine
- Lauan
- Southern yellow pine

Hardwood lumber

- Basswood
- Red oak

SIZES

The product is compatible with any size material selected from among the wood grades suitable for pressure treating.

FINISHES

Wood treated with D-Blaze fire retardant is paintable, stainable and easy to work with common tools.

COLORS

The product is colorless and nonblooming. It will not darken or discolor most woods.

SHAPES

Wood products treated with D-Blaze can be any practical shape.

LIMITATIONS

The product is intended for weather protected applications only. It is not to be used in areas subject to precipitation, wetting, dampness or condensation. All wood products must be kiln dried to a maximum moisture content of 19% for lumber and 15% for plywood. Lower moisture contents may be preferred for cabinetry and millwork.

4. Technical Data

APPLICABLE STANDARDS

ASTM International

- ASTM D3201 Standard Test Method for Hygroscopic Properties of Fire-Retardant Wood and Wood-Base Products
- ASTM D5516 Standard Test Method for Evaluating the Flexural Properties of Fire-Retardant Treated Softwood Plywood Exposed to Elevated Temperatures
- ASTM D5664 Standard Test Method for Evaluating the Effects of Fire-Retardant Treatments and Elevated Temperatures on Strength Properties of Fire-Retardant Treated Lumber
- ASTM E84 Standard Test Method for Surface Burning Characteristics of Building Materials

American Wood-Preservers' Association (AWPA)

- AWPA C20 Structural Lumber - Fire-Retardant Treatment by Pressure Processes
- AWPA C27 (Type A) Plywood - Fire Retardant Treatment by Pressure Process
- AWPA U1, T1, UCFA

National Fire Protection Association (NFPA)

- NFPA 255 Standard Test Method for Surface Burning Characteristics of Building Materials
- NFPA Policy on Design Values for Fire Retardant Treated Lumber

Underwriters Laboratories, Inc. (UL) - UL 723 Tests for Surface Burning Characteristics of Building Materials

U.S. Department of Defense - MIL-L-19140E Lumber and Plywood, Fire Retardant Treated

APPROVALS

Building Officials and Code Administrators International Inc. (BOCA) - BOCA ES No. 95.42

City of Los Angeles, California - RR 24502

City of New York, New York

- Building Code MEA 406
- Building Code MEA 407

Insurance Rating Bureaus

International Conference of Building Officials (ICBO) - ICBO ES 5180

National Evaluation Service - NER 562

Southern Building Code Congress International, Inc. (SBCCI) - SBCCI ES No. 9657

U.S. Bureau of Ships - QPL

National Evaluation Service (NES) - NER 562

ENVIRONMENTAL CONSIDERATIONS

D-Blaze FRT wood products protect against corrosion on galvanized steel truss plates as well as other metal fasteners. Testing has shown that with respect to metal corrosion these FRT products maintain metal finish and metal integrity virtually as well as untreated wood exposed to the same conditions.

PHYSICAL/CHEMICAL PROPERTIES

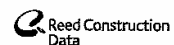
D-Blaze FRT wood has been tested by an independent laboratory in accordance with industry standards to develop strength reduction factors for various use conditions, including roof temperatures up to 150 - 170 degrees F (66 - 77 degrees C). D-Blaze FRT wood shows very low hygroscopicity under relative humidity conditions as high as 95%. It has virtually the same moisture content as untreated wood. Test reports are available to design professionals upon request. For more technical information, see Tables 1 and 2.

FIRE RATING

D-Blaze FRT wood has been tested by Underwriters Laboratories, Inc. (UL), of Northbrook, IL, and has been designated UL



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Chemical Specialties, Inc.

classification FRS, which signifies a flame-spread and smoke developed rating of 25 or less. When tested for 30 minutes, there was no evidence of significant progressive combustion. Each piece of treated material bears a UL classification stamp and meets or exceeds requirements for Class 1 or Class A flamespread ratings.

5. Installation

PREPARATORY WORK

Handle and store product per CSI recommendations. Protect wood products against moisture and dimensional changes.

METHODS

Light sanding or brushing is all that is necessary to ensure proper coating adhesion. Complete installation recommendations are available from the manufacturer.

PRECAUTIONS

Avoid frequent or prolonged inhalation of sawdust from treated wood. When sawing and machining treated wood, wear a dust mask. When power sawing or machining, wear goggles to protect eyes from flying particles. Surfaces must be clean and dry before application. For best results, application should follow manufacturer's recommendations.

BUILDING CODES

Current data on building code requirements and product compliance may be obtained from CSI technical support specialists. Installation must comply with the requirements of all applicable local, state and national code jurisdictions.

6 Availability & Cost

AVAILABILITY

For information on product availability or to identify a local wood preserver, contact



D-Blaze® Fire Retardant Pressure Treated Wood Logo

Chemical Specialties, Inc.

COST

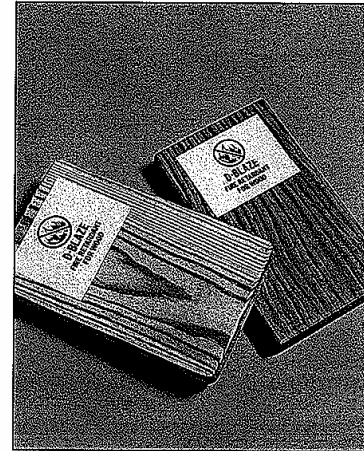
Offers a lower in-place cost than most non-combustible classified building materials. Budget installed cost information may be obtained through the manufacturer.

7. Warranty

Features a 50 year limited warranty. Refer to D-Blaze 50 year limited warranty brochure or consult manufacturer for complete details.

8. Maintenance

No long-term maintenance is required other than to ensure protection from weather and other forms of moisture exposure. Installations which depend on application of approved



D-Blaze® Fire Retardant Pressure Treated Wood

paints or coatings for weather resistance must be periodically repainted to renew moisture protection.

9. Technical Services

A staff of factory trained service personnel offers design assistance and technical support. For technical assistance, contact Chemical Specialties, inc.

10. Filing Systems

- First Source «
- Thomas Register
- The Blue Book
- ARCAT®
- MASTERSPEC «
- Additional product information is available from the manufacturer's website.

TABLE 1 D-BLAZE STRENGTH DESIGN FACTOR FOR LUMBER

	Southern Pine ²	Applicable < 80°F (27°C)			Applicable < 150°F (66°C)	
		Douglas Fir ²	Spruce ²	Other Species ¹	Southern Pine	Other Species ¹
Compressive parallel, Fc	0.93	0.91	0.94	0.91	0.85	0.85
Horizontal shear	1.00	0.97	1.00	0.97	0.86	0.86
Tension parallel	0.77	0.91	0.96	0.77	0.65	0.65
Bending, modulus of elasticity, E	0.88	0.96	0.97	0.88	0.89	0.89
Bending, extreme fiber stress, Fb	0.85	0.87	0.90	0.85	0.79	0.79

¹ Species awarded "FRS" classification by Underwriters Laboratories, Inc. (UL), when tested with D-Blaze FRT chemicals are listed in TYPES in this SPEC-DATA.

² These design value adjustments were determined during a testing program conducted at the Mississippi State University Forest Products Utilization Laboratory. Tests were conducted in accordance with the National Forest Products Association Policy on design values for fire retardant treated lumber products.



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TABLE 2 D-BLAZE PLYWOOD SPAN RATINGS

APA rating	Panel thickness in (mm)	D-Blaze rating
12/0	5/16 (7.9)	12/0
16/0	5/16 (7.9), 3/8 (9.5)	16/0
20/0	5/16 (7.9), 3/8 (9.5)	20/0
24/0	7/16 (11.1), 1/2 (12.7)	24/0
24/16	7/16 (11.1), 1/2 (12.7)	24/16
32/16	15/32 (11.9), 1/2 (12.7)	24/16
32/16	5/8 (15.9)	32/16
40/20	5/8 (15.9), 19/32 (15.1)	32/20
40/20	3/4 (19.1), 7/8 (22.2)	40/20
48/24	23/32 (18.3), 3/4 (19.1)	40/24
48/24	7/8 (22.2)	48/24

- For temperatures up to 170°F (77°C).
- 5/16" or 3/8" (7.9 or 9.5 mm) thicknesses not for roof applications. Use only plywood manufactured per PSI 83, Group 1, stress level 2 with exterior glue. Designed for 30 psf (146 kg/m²) live load plus 4.5 psf (22 kg/m²) dead load.

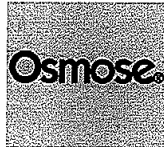


A1.5 FirePRO®



FIRE RETARDANT TREATMENT 06073

Osmose, Inc.



1. Product Name

FirePRO® Brand Fire Retardant Treated Wood (FirePRO FRTW)

2. Manufacturer

Osmose, Inc.
Wood Preserving Division
P.O. Drawer O
1016 Everee Inn Road
Griffin, GA 30224-0249
(800) 241-0240
(770) 233-4200
Fax: (770) 229-5225
E-mail: treatedwood@osmose.com
www.osmose.com
www.timberspecialties.com

3. Product Description

BASIC USE

FirePRO® FRTW is lumber and plywood pressure impregnated with FirePRO Interior Type A High Temperature Tested (HT) fire retardant chemicals. Independent testing performed in accordance with the latest industry standards has shown FirePRO FRTW to exhibit exceptional fire performance and superior strength durability, corrosion and hygroscopic properties when compared to the untreated wood used in these tests.

FirePRO FRTW is typically permitted for interior, aboveground applications such as roof systems, studs, flooring, joists, sill plates (when not in direct contact with the ground), blocking and furring and other interior applications.

FirePRO FRTW is treated with a fire retardant that contains borates and is an EPA registered pesticide. This offers FirePRO FRTW protection from termites and decay fungi.

Key product values include:

- Termite and decay protection
- Independently tested
- Superior strength durability
- Low hygroscopicity
- Highly cost effective
- Low smoke development values
- Corrosion resistant
- Pressure treated (not a coating)
- UL classified (FR-S rated) for surface burning characteristics
- Building code compliant

- 50 year limited warranty
- Quality monitored by independent, third party inspection agency

COMPOSITION & MATERIALS

FirePRO FRTW is a unique, new generation, patented fire retardant based on proprietary Osmose technology.

TYPES

FirePRO fire retardant treated lumber is available in a wide range of softwood species including:

- Southern pine
- Red pine
- Douglas fir
- Ponderosa pine
- Western hemlock
- White fir
- Alpine fir
- Hem-fir
- Lodgepole pine
- Balsam fir
- White spruce
- Jack pine
- Spruce-pine-fir
- Englemann spruce
- Red spruce
- Black spruce

FirePRO fire retardant treated plywood is available in Douglas fir.

IDENTIFICATION

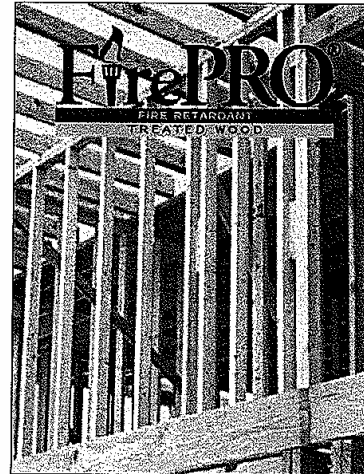
All lumber and plywood treated with FirePRO fire retardant chemicals shall be identified with the grade mark of an approved quality assurance agency. FirePRO FRTW bears the Underwriters Laboratories, Inc. (UL) stamp, the producer's name and location, the flamespread rating or FR-S designation, the statement "TP MONITORED STD FP-00" and the National Evaluation Report number (NER-577), for field identification.

LIMITATIONS

Review the test data on FirePRO FRTW to determine if it is acceptable for the intended end use. FirePRO FRTW is typically specified for use where the building code jurisdiction permits the use of wood or fire retardant treated wood.

When designing any structure, take into account environmental, duration of load and other factors as set forth in the NDS and all other applicable design standards, codes, etc. This data sheet should be regarded as an adjunct to, and not a substitute for, these mandatory and historical references.

FirePRO FRTW is not permitted for applications where the material may be exposed to



FirePRO® FRTW structural framing

precipitation, direct wetting or regular condensation, and it should not be used in contact with the ground.

4. Technical Data

APPLICABLE STANDARDS

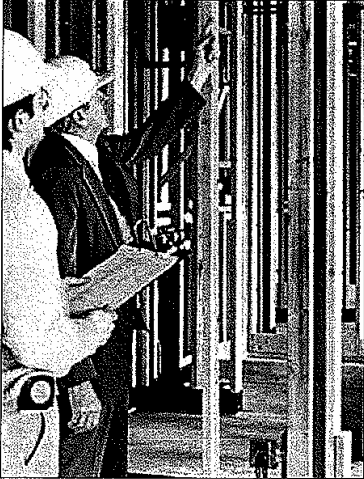
ASTM International

- ASTM D3201 Standard Test Method for Hygroscopic Properties of Fire-Retardant Wood and Wood-Base Products
- ASTM D3359 Standard Test Methods for Measuring Adhesion by Tape Test
- ASTM D5516 Standard Test Method for Evaluating the Flexural Properties of Fire-Retardant Treated Softwood Plywood Exposed to Elevated Temperatures
- ASTM D5664 Standard Test Method for Evaluating the Effects of Fire-Retardant Treatments and Elevated Temperatures on Strength Properties of Fire-Retardant Treated Lumber
- ASTM D6305 Standard Practice for Calculating Bending Strength Design Adjustment Factors for Fire-Retardant-Treated Plywood Roof Sheathing
- ASTM D905 Standard Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading
- ASTM E84 Standard Test Method for Surface Burning Characteristics of Building Materials
- ASTM E162 Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source



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FirePRO® FRTW meets major model building codes.

- ASTM E662 Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials
- ASTM E1354 Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter

American Wood-Preservers' Association (AWPA)

- AWPA C20-93 Structural Lumber - Fire - Retardant Treatment by Pressure Processes
- AWPA C27-93 Plywood - Fire-Retardant Treatment by Pressure Processes
- AWPA E1 Standard Method of Laboratory Evaluation to Determine Resistance to Subterranean Termites
- AWPA E6 Standard Method for Determining the Equilibrium Moisture Content of Fire-Retardant Treated Wood
- AWPA E12 Standard Method for Determining Corrosion Resistance of Metal in Contact with Treated Wood

American National Standards Institute (ANSI) - ANSI/TPI 1-1995 National Standard for Metal Plate Connected Wood Truss Construction

Boeing Support Standard (BSS) - BSS 7239 Gas Analysis and Smoke Density Test

National Fire Protection Association (NFPA) - NFPA 255 Standard Method of Test of Surface Burning Characteristics of Building Materials

Underwriters Laboratories, Inc. (UL) - UL 723 Standard for Safety for Surface Burning Characteristics of Building Materials

NYS Mod. Pittsburgh Protocol on Smoke Toxicity

Copies of tests are available upon request.

APPROVALS

National Evaluation Report NER-577 indicating flamespread, smoke development, strength durability, corrosion and hygroscopic properties

New York City Materials and Equipment Acceptance Numbers MEA 137-00-M (lumber), MEA 136-00-M (plywood)

City of Los Angeles Research Report Number RR 25442

Consult manufacturer for current information on approvals by code bodies and other industry entities.

ENVIRONMENTAL CONSIDERATIONS

Historically, fire retardants have utilized phosphorus based compounds. FirePRO products contain no phosphorus based compounds.

PHYSICAL/CHEMICAL PROPERTIES

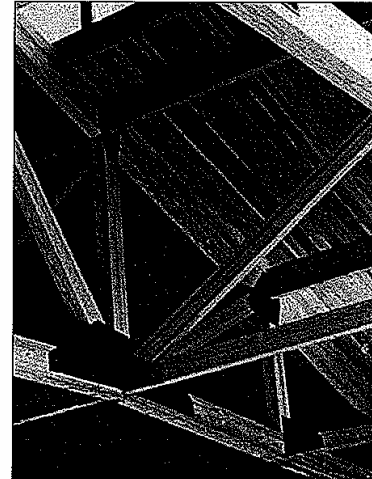
Test reports are available to design professionals upon request.

Strength Durability

The structural durability of FirePRO brand fire retardant treated lumber and plywood has been independently tested according to the latest and most stringent versions of ASTM strength durability standards. When tested according to ASTM Standards D5564-95 (lumber) and D5516-96 (plywood), FirePRO brand fire retardant treated wood showed no signs of significant degrade over untreated wood following exposure to the severe test conditions.

This structural performance testing demonstrates that lumber and plywood treated with FirePRO chemicals show no indications and no significant potential to experience high temperature strength reductions or exhibit thermal degradation when exposed for extended periods to elevated temperatures and humidity.

The National Design Specifications (NDS), Wood Handbook, and other publications have cautioned against the use of any wood product in environments exceeding 150 degrees F (66 degrees C). Based on the strength data generated at the USDA Forest Products Laboratory, professional engineers have calculated design values and span adjustments to modify the untreated design



FirePRO® FRTW roof decking and trusses

values for lumber and span ratings for plywood (see Tables 1 and 2).

Corrosivity

The corrosivity of FirePRO FRTW has been evaluated in accordance with AWWA Standard E12-94 for a variety of metals. The corrosion rates for carbon steel, galvanized steel, stainless steel, aluminum, red brass and copper are not significantly increased by FirePRO fire retardant chemicals when the treated wood products are used as recommended by the manufacturer and properly sized for the materials selected.

Use conventional metal fasteners in contact with FirePRO FRTW: 2024-T3 aluminum, SAE 1010 steel, hot dipped zinc galvanized steel, stainless steel, copper or red brass.

Hygroscopicity

Hygroscopicity testing conducted by independent laboratories has confirmed that compared to untreated wood, FirePRO FRTW does not pick up excessive moisture even under the humid test conditions of the standards developed for fire retardant treated wood. Consequently, FirePRO fire retardant treated lumber and plywood qualifies as Interior Type A High Temperature Tested (HTT) fire retardant treated wood in accordance with Sections 2.2.2.1 of AWWA Standards C20 and C27, when tested at 92% relative humidity.

FIRE PERFORMANCE

All FirePRO FRTW is recognized as having flamespread and smoke development ratings of 25



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or less when subjected to ASTM E84 surface burning characteristics tests of 30 minutes duration without evidence of significant progressive combustion. Consequently, wood treated with FirePRO fire retardant carries the superior UL FR-S classification for surface burning characteristics. Independent combustion toxicity testing has shown that smoke generated by FirePRO FRTW is no more toxic than smoke produced by untreated wood.

5. Installation

PREPARATORY WORK

Handle and store product according to Osmose recommendations. Store protected from weather and direct wetting.

METHODS

Structural systems, which include FirePRO fire retardant treated lumber or plywood, should be designed and installed in accordance with the requirements of the building code authority having jurisdiction, using the appropriate lumber design adjustment factors and plywood spans from tables provided in manufacturer's literature. Ventilation must be provided in compliance with the applicable codes.

Under normal temperature and humidity conditions, latex and oil based paints, as well as water and solvent-based stains, can be used with FirePRO FRTW. If prolonged exposure to high humidity conditions is expected, special surface preparation procedures, including the use of an appropriate primer, are recommended. Before application of any finish, the wood surface should be lightly sanded, cleaned and dry. For best results, always follow the coating manufacturer's label instructions. Complete installation and use recommendations are available from the manufacturer.

PRECAUTIONS

Exposure to precipitation during shipping, storage and installation should be avoided.

Typical joining cuts, end cuts and drilled holes will not adversely affect the fire performance of FirePRO FRTW and no field treatment is required to maintain flamespread ratings. However, ripping or milling of FirePRO lumber is not permitted, as these operations could adversely affect the surface burning characteristics. FirePRO plywood can be ripped as required.

TABLE 1 STRENGTH DESIGN FACTORS FOR FIREPRO LUMBER ¹

Strength design factor	Southern pine	Douglas fir	Spruce	Other available species
Compression parallel to grain	1.00	1.00	1.00	1.00
Tension parallel to grain	0.82	0.83	0.99	0.82
Horizontal shear	0.97	0.93	0.88	0.88
Bending: MOE	0.95	0.99	0.94	0.94
Bending: extreme fiber stress, FB	0.84	0.97	0.89	0.84

¹ Compared to untreated lumber applicable at temperatures up to 180°F (82°C).

TABLE 2 FIREPRO PLYWOOD SPAN RATINGS ¹

Panel thickness	APA rating	FirePRO rating
5/16" (7.9 mm)	12/0	12/0
5/16", 3/8" (7.9, 9.5 mm)	16/0	16/0
5/16", 3/8" (7.9, 9.5 mm)	20/0	20/0
3/8", 7/16", 1/2" (9.5, 11.1, 12.7 mm)	24/0	24/0
7/16", 1/2" (11.1, 12.7 mm)	24/16	24/16
15/32", 1/2" (11.9, 12.7 mm)	32/16	32/16
5/8" (15.9 mm)	32/16	32/16
5/8", 19/32" (15.9, 15.1 mm)	40/20	32/20
3/4", 7/8" (19.1, 22.2 mm)	40/20	40/20
23/32", 3/4" (18.3, 19.1 mm)	48/24	48/24
7/8" (22.2 mm)	48/24	48/24

¹ Span ratings are for rated sheathing applicable at temperatures up to 170°F (77°C).

BUILDING CODES

Current data on building code requirements and product compliance may be obtained from Osmose technical support specialists. Installation must comply with the requirements of applicable local, state and national code jurisdictions.

6. Availability & Cost

AVAILABILITY

FirePRO FRTW is produced by independently owned and operated wood preserving facilities.

COST

Budget installed cost information may be obtained from a local FirePRO distributor, retailer or supplier.

7. Warranty

The only warranties made by Osmose are set forth in the "Osmose FirePRO 50 Year Limited Warranty Agreement." Osmose makes no other warranties, express or implied, of merchantability, fitness for a particular purpose or otherwise.

For additional information on warranty conditions, duration and remedies, contact manufacturer.

8. Maintenance

There are no specific maintenance requirements for properly installed FirePRO FRTW; however, the product should be kept dry during service life.

9. Technical Services

For technical assistance, contact a dealer, supplier, FirePRO processing facility or Osmose, Inc.

10. Filing Systems

- First Source™
- MANU-SPEC™
- Sweet's Catalog Files
- Additional product information is available from the manufacturer upon request.



A.2 Typical Residential Floor Truss Loading

Determine the Loading of a Residential Floor Truss

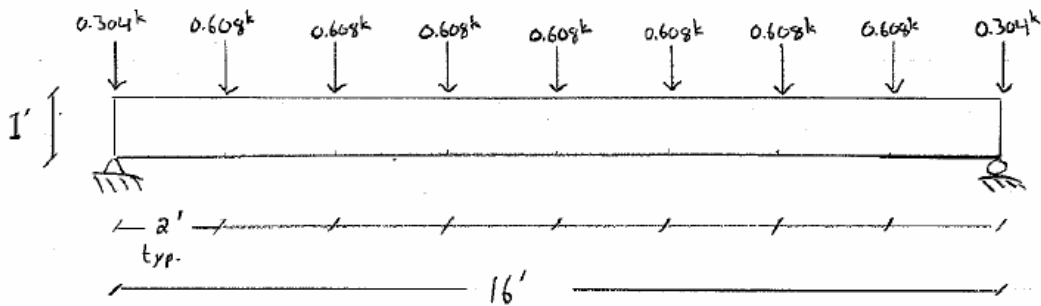
Assume: 16' x 16' room, 24" c/c truss spacing (4' tributary width)

No. 1 Southern Pine: $E = 1700 \text{ ksi}$
 $F_c = 1850 \text{ psi}$ (NDS Supplement 2001 Ed.)
 $F_T = 1050 \text{ psi}$

Live Load = 40 psf (IBC 2003)

Dead Load = 10 psf (Conservative when compared to TJI Joist Specifier's Guide 2027, Oct. 2003 for 1/2" plywood sheathing, Carpet + Pad, and 1/2" gypsum board; $\approx 5 \text{ psf}$)

$$w_u = 1.2(10 \cdot 4) + 1.6(40 \cdot 4) = 304 \text{ lb/ft.}$$



A.3 Truss-4 Sample Input and Output Files

Input File

Thesis Truss Analysis-Residential Parallel Chord Floor Truss, Type II

11 19 1 2 5

Joint Coordinates

1	0.0	0.0
2	0.0	12.0
3	24.0	0.0
4	48.0	12.0
5	72.0	0.0
6	96.0	12.0
7	120.0	0.0
8	144.0	12.0
9	168.0	0.0
10	192.0	12.0
11	192.0	0.0

Material Data

1	1700.0
---	--------

Member Data

1	1	2	5.25
2	2	4	8.25
3	2	3	5.25
4	1	3	8.25
5	3	4	5.25
6	4	6	8.25
7	4	5	5.25
8	3	5	8.25
9	5	6	5.25
10	6	8	8.25
11	6	7	5.25
12	5	7	8.25
13	7	8	5.25
14	8	10	8.25
15	8	9	5.25
16	7	9	8.25
17	9	10	5.25
18	9	11	8.25
19	10	11	5.25

Support Data

1	1	1
11	1	1

Joint Loads

2	0.0	-1.7
4	0.0	-3.4

6	0.0	-3.4
7	0.0	-3.4
8	0.0	-3.4
10	0.0	-1.7

Output File

Thesis Truss Analysis-Residential Parallel Chord Floor Truss, Type II

NUMBER OF JOINTS = 11
 NUMBER OF MEMBERS = 19
 NUMBER OF MATERIALS = 1
 NUMBER OF SUPPORT JOINTS = 2
 NUMBER OF LOADED JOINTS = 5

JOINT DATA

JOINT	X	Y	RESTRAINTS	
1	.000	.000	1.	1.
2	.000	12.000	0.	0.
3	24.000	.000	0.	0.
4	48.000	12.000	0.	0.
5	72.000	.000	0.	0.
6	96.000	12.000	0.	0.
7	120.000	.000	0.	0.
8	144.000	12.000	0.	0.
9	168.000	.000	0.	0.
10	192.000	12.000	0.	0.
11	192.000	.000	1.	1.

MEMBER DATA

MEMBER	J1	J2	AX	E
1	1.	2.	5.250	1700.0
2	2.	4.	8.250	1700.0
3	2.	3.	5.250	1700.0
4	1.	3.	8.250	1700.0
5	3.	4.	5.250	1700.0
6	4.	6.	8.250	1700.0
7	4.	5.	5.250	1700.0
8	3.	5.	8.250	1700.0
9	5.	6.	5.250	1700.0
10	6.	8.	8.250	1700.0
11	6.	7.	5.250	1700.0

12	5.	7.	8.250	1700.0
13	7.	8.	5.250	1700.0
14	8.	10.	8.250	1700.0
15	8.	9.	5.250	1700.0
16	7.	9.	8.250	1700.0
17	9.	10.	5.250	1700.0
18	9.	11.	8.250	1700.0
19	10.	11.	5.250	1700.0

JOINT LOADS

JOINT	WX	WY
2	.000	-1.700
4	.000	-3.400
6	.000	-3.400
7	.000	-3.400
8	.000	-3.400

JOINT DISPLACEMENTS

JOINT	X-DISP	Y-DISP
1	.00000	.00000
2	.15556	-.01086
3	-.03927	-.49636
4	.11193	-.89460
5	-.03055	-1.22427
6	.00429	-1.33866
7	.01891	-1.30304
8	-.12080	-.96613
9	.03927	-.53738
10	-.17025	-.00971
11	.00000	.00000

MEMBER FORCES (TENSION POSITIVE)

MEMBER	FORCE
1	-8.075
2	-12.750
3	14.255
4	-22.950
5	-14.255
6	-31.450
7	6.652

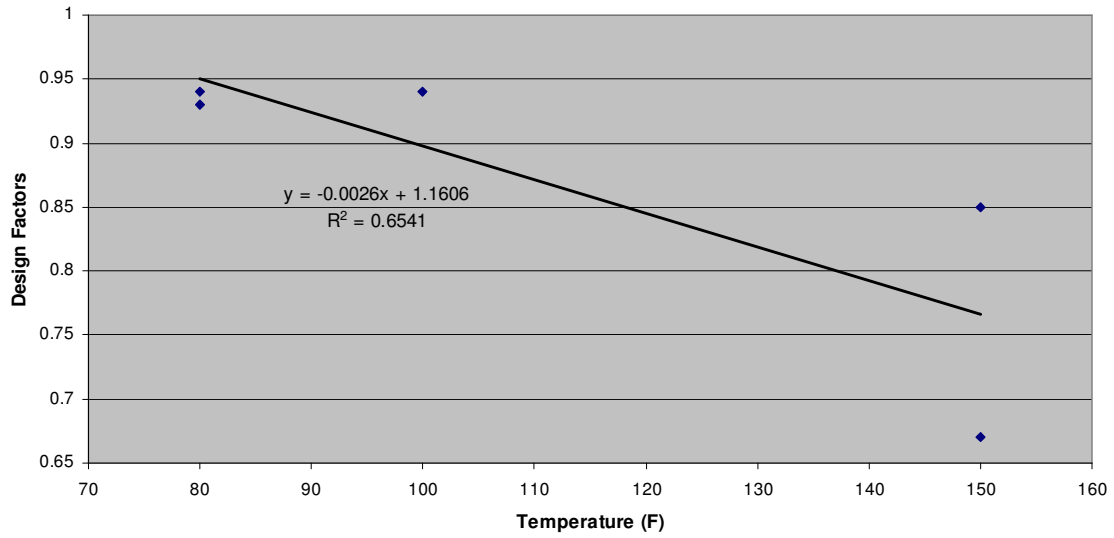
8	2.550
9	-6.652
10	-36.550
11	-.950
12	14.450
13	8.553
14	-14.450
15	-16.156
16	5.950
17	16.156
18	-22.950
19	-7.225

REACTIONS

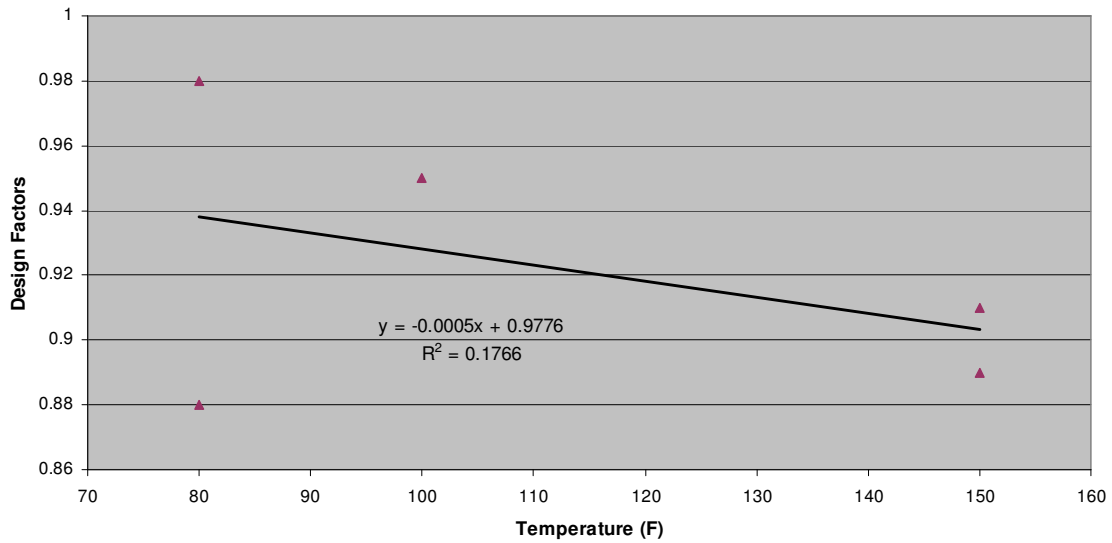
JOINT	RX	RY
1	22.950	8.075
11	-22.950	7.225

A.4 Strength Properties of FRTW vs. Temperature

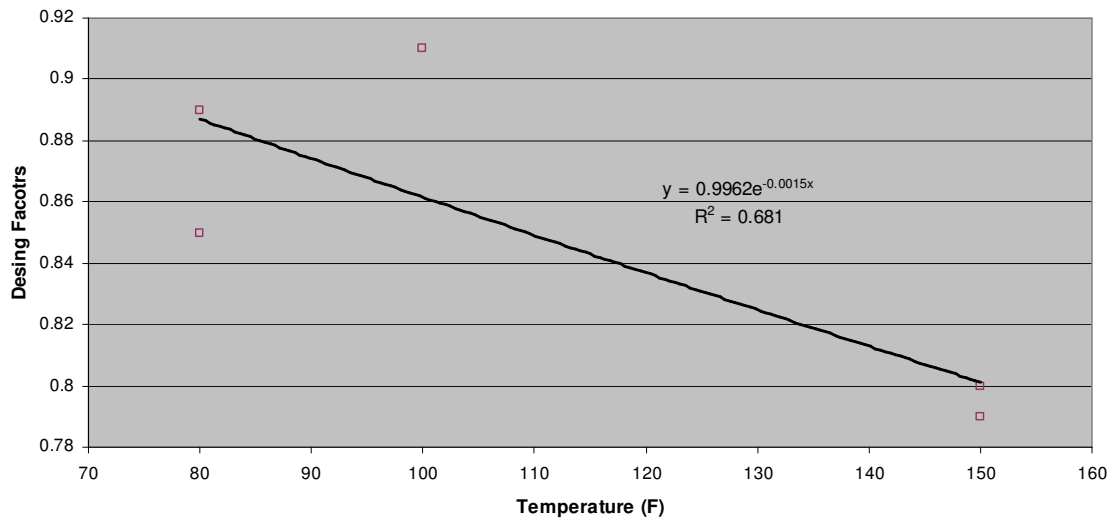
Percent Compression Capacity Vs. Temperature



Percent MOE Vs. Temperature



Percent Bending Capacity Vs. Temperature



A.5 Residential Fire Ignition Sources

The following statistics describe the most common ignition sources in residential fires that killed older adults, age 65 and up, which accounted for 27% of all fire deaths in this occupancy in 2002. The information is shown below in Figure 15.

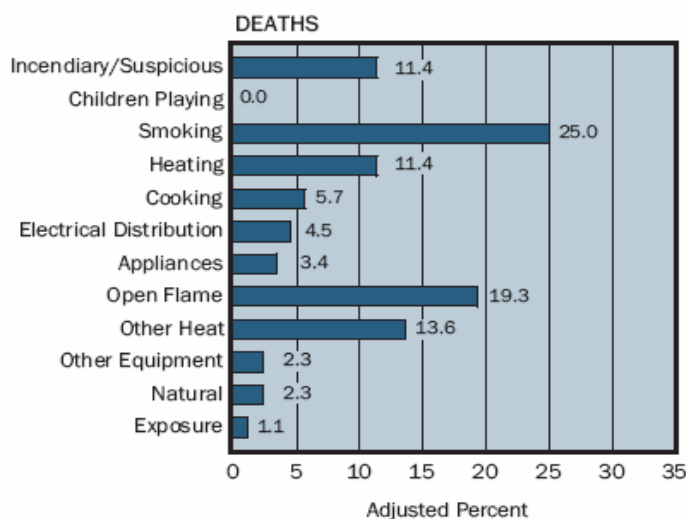


Figure 15: Causes of residential fires with older adult casualties (U.S. Fire Administration June, 2005)

The most common materials ignited first in fire scenarios where adults, ages 65 and older, were killed were upholstered furniture, worn clothing, and bedding with a combined 40% of all materials. Smoking was the primary heat source for the ignition of both furniture and bedding.

Furthermore, in the 65 and older category, arson was the most deadly ignition source causing 22% of the total number casualties while smoking was a close number two with 21% followed by open flames at 15%. (U.S Fire Administration June, 2005)

Child fire deaths, children aged 14 and under, account for 15% to 20% of the nations total. Data that shows common ignition sources in scenarios that resulted in a child death is reported in Figure 16.

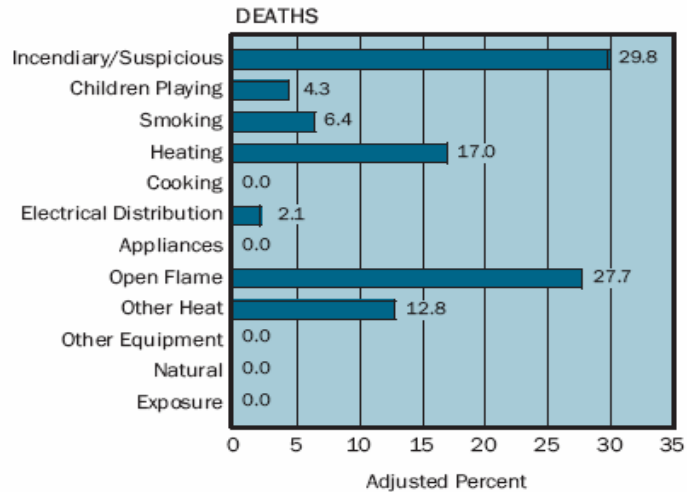


Figure 16: Causes of residential fires with child fatalities (U.S. Fire Administration April, 2005)

Again, as with the 65 and older age group, bedding and upholstered furniture were most commonly the first items ignited (38%) with lighters and candles being their primary ignition sources. Arson, as with the 65 and older group, the number one ignition source causing death in 2002 (30%) with open flames number two (28%). (U.S. Fire Administration April, 2005)

Older adults and young children are among the most vulnerable people in American society. When someone from these categories dies, especially a child, it is a severely devastating event. It is believed that by reducing the number of deaths in these two categories, since they are the most vulnerable, deaths from other demographics will also be reduced, creating a nation safer from fire.

A.6 Alternative Fire Scenario Using CFAST

Consolidated Model of Fire Growth and Smoke Transport (CFAST) is a two-zone fire model developed by NIST that is publicly available on their website:

<http://fast.nist.gov/>. Though this program has multiple capabilities, for the purpose of this thesis, it was used to develop time/temperature and heat flux histories at the ceiling in a scenario developed to be representative of a typical residential living room.

CFAST uses a system of ordinary differential equations derived from the fundamental principles of conservation of mass, energy, and the ideal gas law. These equations predict values as a function of time such as flame height, ceiling layer thickness, pressures, temperatures, and mass of entrained species.

A fundamental limitation of CFAST, which is common to zone models, is that it approximates the ceiling layer, plume, and lower gas layer as straight-edged, uniform temperature volumes, which is not the case in a real fire scenario, giving rise to a 10% spatial error on calculation of the layer thickness (Jones 2004). Also, it is best used under circumstances where the length and width of the room are similar and the ceiling is kept within the limits described in Table 20. If one dimension becomes much larger than the other, the space will essentially be a corridor, and because corridors have much different flow patterns than that of a normal room, CFAST has a corridor flow option that should be used accordingly. If the ceiling is too tall compared to the floor dimensions, at some point the width of the plume at a given height may become equal to the width of the room and the governing limiting assumptions will fail. It was found experimentally that in elevator shafts, when the plume width reaches the walls, combustion products and air mix

completely, creating a one-zone model necessary (Jones 2004). Dimensional limitations that must be considered are summarized below in Table 20. (Jones 2004)

Table 20: Recommended CFAST compartment dimension limits

Ratio	Acceptable	Special Consideration Needed	Corridor Flow
$(\text{Length/Width})_{\text{max}}$	$L/W < 3$	$3 < L/W < 5$	$5 < L/W$
$(\text{Length/Height})_{\text{max}}$	$L/H < 3$	$3 < L/H < 6$	$6 < L/H$
$(\text{Width/Height})_{\text{min}}$	$W/H > 0.4$	$0.4 > W/H > 0.2$	$0.2 > W/H$

A summary of the necessary input variables for the CFAST simulation is shown below in Table 21.

Table 21: Summary of CFAST inputs for the delayed ignition scenario

CFAST Analysis						
	Description	Value		Description	Location (XxYxZ)	Ignition Time
Environmental and Geometrical Input Parameters	Simulation Time	3600sec.	Design Fires	Bunsen	8.5'x8'x0'	0sec
	Output Interval	30sec.		Sofa	8'x8'x0'	5sec
	Initial Temperature	68°F		Curtains	15.25'x8'x4.5'	60sec
	Initial Pressure	1atm		Upholstered Chair	4'x8'x0'	180sec
	Relative Humidity	50%		Curtains	8'x15.25'x4.5'	180sec
	Power Law	0.16(default)		TV set	8'x2'x0'	300sec
	Compartment Dimensions	16'x16'x9' (XxYxZ)		Upholstered Chair	12.8'x12.8'x0'	300sec
	Wall & Ceiling Materials	All 1/2" gypsum board				
	Horizontal Flow Vent	6'x3' doorway (always open)				

Remaining consistent with the floor system design, a 16 foot by 16 foot room was used along with an assumed ceiling height of 9 feet. These dimensions fit well inside the limitations described in Table 20, therefore no special considerations were needed, ordinary room flow patterns could be assumed, and a two-zone model was legitimate. Wall and ceiling materials were chosen to be gypsum board because this is the most common finish covering used in light-weight residential construction. The doorway was centered on the westerly wall of the simulated compartment. Figure 17 below shows a sketch of the model used in this simulation. In this case, the yellow markers on the

ceiling represent data collecting targets, whose locations were defined by the user; while all others yellow markers are design fires.

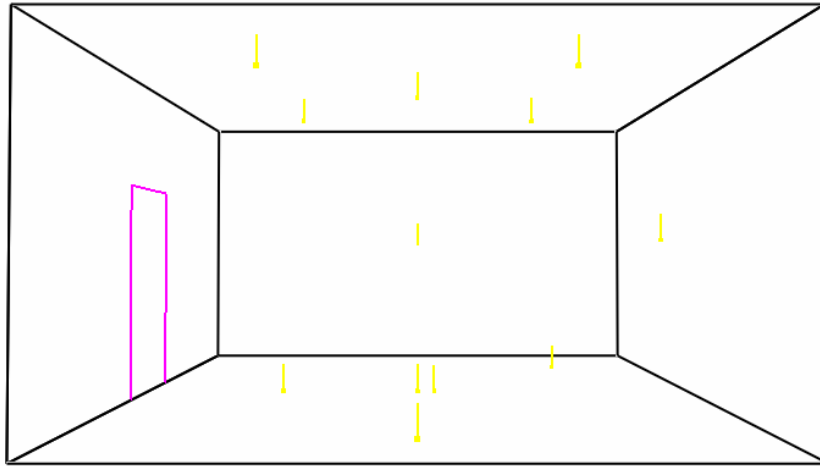


Figure 17: Room layout of the CFAST model used, provided by a visual package called Smokeview™

Design fires were chosen in to reflect the types of combustibles most commonly involved in residential fires. Appendix A.5 Residential Fire Ignition Sources describes statistics on this topic. As discussed in Appendix A.5, upholstered furniture is one of the most common materials involved in residential fires that cause injury. The bunsen was used to simulate an ignition source. CFAST has a limited number of combustible items to choose from that have predefined heat release rate (HRR) curves. Because the bunsen was the item with smallest intensity HRR curve that exhibited a growth and decay period, it was the best fit for its purpose in this simulation. Other items were chosen to try to simulate what may be in a typical living room. Ignition times were chosen to try and simulate the progression of a fire from ignition source, to the item it impinges upon, then to surrounding combustible materials. Item locations were, for the most part, arbitrary.

In order to obtain the worst case time/temperature and time/heat flux scenarios to be used in the thermal analysis, an array of information collecting targets were created in

the model. Target information is summarized in Table 22 below. Locations were chosen to be above and surrounding the upholstered couch in the center of the room. Because it is the first item ignited, and has the most intense heat release rate curve, as defined by the CFAST program, it was assumed that these locations would yield the worst-case time/temperature curve. Placing targets close to the walls of the room was avoided because many zone models contain algorithms for reflected heat flux from the hot surface of the walls back to the room. If the target was too close, this may change the results considerably, and because this complication is beyond the scope of this project, targets were kept towards the center of the room.

Table 22: Description of additional targets created in CFAST analysis. Locations are typical for all scenarios.

Target Descriptions			
<u>Target</u>	<u>Location (XxYxZ)</u>	<u>Material</u>	<u>Analysis Type</u>
1	8'x8'x9'	1/2" gypsum board	Thermally Thin
2	4'x12'x9'	1/2" gypsum board	Thermally Thin
3	12'x4'x9'	1/2" gypsum board	Thermally Thin
4	12'x12'x9'	1/2" gypsum board	Thermally Thin
5	4'x4'x9'	1/2" gypsum board	Thermally Thin

Multiple scenarios were run to generate the most intensive situation. Model variations included making all items burn at the same time, changing wall and ceiling materials, changing the fire to be ventilation limited, and using a thermally thick analysis. After evaluating all data, the most severe time/temperature exposure was compared to the ASTM E-119 curve. The scenario using delayed ignition, gypsum ceiling, ventilation unlimited, and thermally thin analysis was chosen and is summarized below in Figure 18.

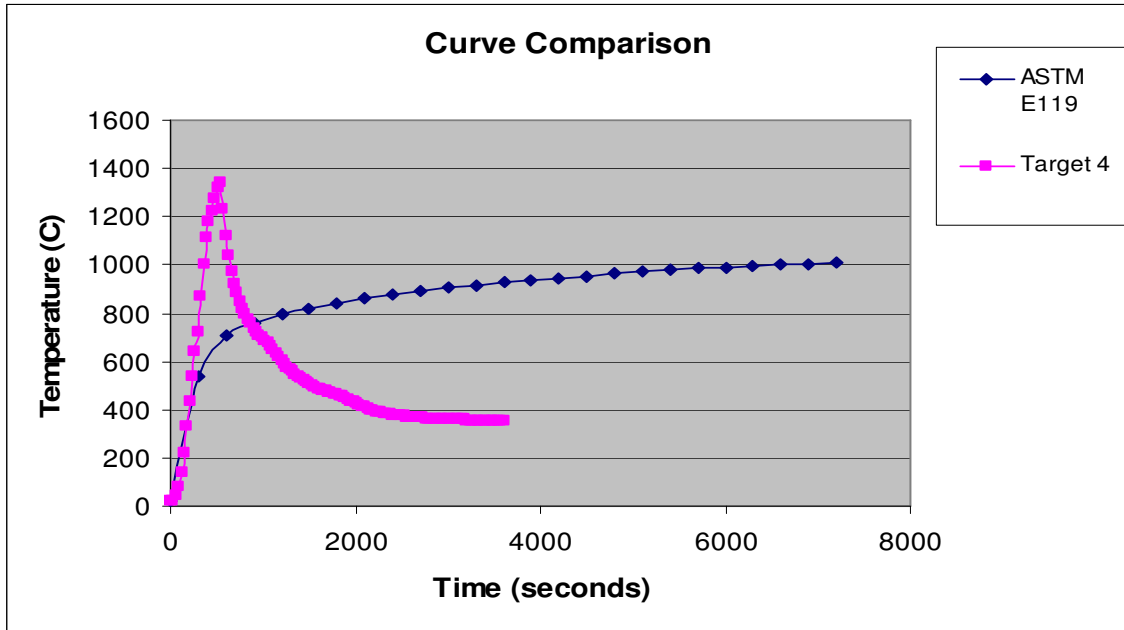


Figure 18: Most intense CFAST curve compared with the ASTM E-119 standard exposure.

A.7 Alternative Model for Char Formation

Strength reduction occurs in two fashions for the wood members, charring and thermal degradation before charring. The effect of charring is the most well known and documented of these behaviors. Empirical formulas have been established for charring, and they are shown below.

$$\beta_n = 0.4 + \left(\frac{280}{\rho} \right)^2; \rho = kg / m^3 \quad (19) \text{ (Buchanan 2001)}$$

$$\beta = \frac{2.58 \beta_n}{t^{0.187}} \quad (20) \text{ (Buchanan 2001)}$$

$$c = \beta \cdot t \quad (21) \text{ (Buchanan 2001)}$$

Where β_n is the nominal char rate in millimeters per minute, β is the effective char rate, t is the exposure time in minutes, and c is the char depth in millimeters. Because exposure time is based upon the ASTM E-119 standard curve, this information can be coupled the respective time/temperature data to determine the loss of section in the lumber during the exposure.

A.8 Combined Stress Index

A combined stress index (CSI) could be used as the failure criteria of the wood sections and plate element. This particular CSI was taken from a paper by White, Cramer, and Shrestha called “Fire Endurance Model for a Metal-Plate-Connected Wood Truss”.

This failure model includes a CSI for compression, tension, and a Plate Failure Index (PFI) that could be used to represent the integrity of the interaction between the wood and the plate. If the CSI or PFI is greater than or equal to 1.0, the section will fail. The equations below describe the indexes.

Compression:

$$CSI = \left(\frac{f_c}{F_{c1}} \right) + \left(\frac{f_b}{\theta_c \cdot F_b} \right) \quad (22)$$

$$\theta_c = 1 - \frac{f_c}{F_{c3}}$$

$$F_{c1} = \frac{F_{c2} + F_{c3}}{1.6} - \sqrt{\left(\frac{F_{c2} + F_{c3}}{1.6} \right)^2 - \left(\frac{F_{c2} * F_{c3}}{0.8} \right)} \quad (23)$$

$$F_{c3} = \frac{0.822 E}{(L / d)^2}$$

Where f_c is the member compressive stress, f_b is the member bending stress, F_b is the member bending strength (assuming complete lateral support), F_{c2} is member crushing strength, F_{c3} is the member buckling stress, E is the elastic modulus, L is the member length, d is the member depth, and θ_c is a parameter that captures the severity of the buckling stress in relation to the member compressive stress used to reduce F_b since the members are not actually continuously supported.

Tension:

$$CSI = \left(\frac{f_t}{F_t} \right) + \left(\frac{f_b}{F_b} \right) \quad (24)$$

Where f_t is the member tensile stress and F_t is the member tensile strength.

Plate Failure:

$$PFI = 1 - \frac{K_1}{K_0} \quad (25)$$

Where K_1 is the final tangent stiffness value of the plate-wood connection, and K_0 is the original tangent stiffness value of the plate-wood connection.